Restoration of the Salton Sea

Volume 1: Evaluation of the Alternatives

Appendix 1G: Predicted Sediment Distribution and Resuspension in Proposed Alternatives for the Salton Sea

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Predicted Sediment Distribution and Resuspension in Proposed Alternatives for the Salton Sea

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Executive Summary

The distribution of sediments and their potential for resuspension have significant influence on internal nutrient recycling, sediment oxygen demand, macrophyte and benthic community distributions, and other processes in lakes. The distribution and resuspension of sediment within a lake basin are generally recognized to be a function of wind speed, fetch, water depth, basin slope, particle size, sediment cohesiveness and other factors.

In a recent study, Anderson et al. (in review) evaluated a series of models and compared predicted sediment distributions with that found in the Salton Sea. The dynamic ratio model of Hakanson (1982) was found to reasonably estimate the area of erosion (i.e., the zone of regular resuspension and no significant net sediment deposition) plus transportation (where sediment accumulation is interrupted by infrequent periods of resuspension) and therefore also the area of sediment accumulation (where no resuspension or further focusing occurs). The model predicted sediment accumulation in the north basin, in good agreement with observed organic C distribution that exceeded 10% (dry-weight basis) there. By contrast, organic C concentrations rarely exceeded 5% in the south basin.

The dynamic ratio model of Hakanson (1982) was used to compare the relative distribution of the erosional, transportational and depositional zones within the different alternatives. The surface areas and maximum depths (Zmax) for the different alternatives were taken from the draft Value Planning Study (USBR, 2005). Volumes and mean depths (Zmean) were estimated from hypsographic curves for the Sea. Mean depths and surface areas were then inputted into the dynamic ratio model to predict the percent area subject to erosion, transportation and accumulation for each of the alternatives (at both 5 and 95% values as described in the Value Planning Study).

The North Lake-Dam (NL-D), South Lake-Dam (SL-D) and revised Salton Sea Authority (SSA) alternatives were the deepest of the alternatives (Zmax of 11.6 – 13.7 m, compared with 4 – 9.1 m maximum depths for the other alternatives); combined with the shorter fetch and lower surface areas (35 – 47 % of the surface area of the current Sea), these alternatives were predicted to have

greater relative areas of accumulation (27.4 – 35.9 %) when compared with either the current Sea (12.1%) or the other shallower alternatives, where only 0 – 5.7% of the sediment areas were predicted to be sheltered from any wind-driven resuspension. The proportion of the sediment area prone to regular resuspension (i.e., the erosional zone) was also lower in the NL-D, SL-D and SSA alternatives than either the current Sea or the other (shallower) alternatives. The smaller cross-sectional area and shorter fetch lowered the amount of wind energy inputted to the lake(s); thus for these (deeper) alternatives, less resuspension than the current Sea and the other shallower alternatives is expected. Reduced resuspension will lower the amount of phosphorus, NH_3, and H_2S released to the epilimnion or the mixed portion of the water column, reduce nonalgal turbidity, lower oxygen consumption, and enhance Se reduction and burial. The reduced mixing in these deeper impoundments indicates more extensive stratification, however, so increased accumulation of nutrients and H_2S within the hypolimnia is likely. Thus, upon mixing, very low DO concentrations and high H_2S and NH_3 concentrations may be present throughout the water column in these deeper alternatives. This may result in widespread fish kills and related ecological problems, as well as strong odor production, each fall.

Separate calculations were also made using wave-theory (e.g., Carper and Bachmann, 1984) and meteorological data at the Sea to estimate wave periods, wavelengths and potential resuspension depths as a function of fetch. The frequency of occurrence of different wind speeds were extracted from hourly average CIMIS data and recast in probabilistic terms so that the frequency of mixing to various depths could be estimated. The shorter fetch lengths of the alternatives were predicted to lower their wave-mixed depths relative to that of the present Sea. For example, wave-induced mixing and resuspension was predicted to 7.1 m depth for the NL-D alternative about 1% of the time, while mixing to 8.8 m was predicted for the present Sea at this same frequency. This finding is consistent with the predictions using the dynamic ratio model of Hakanson (1982), where lower critical depths and larger aE+T were predicted for the north lake (and south lake) alternatives relative to the present Sea (and the other, larger basins).

Introduction

The distribution of sediments, their properties, and their potential for resuspension have significant influence on water quality, as well as benthic and pelagial ecology. Internal nutrient recycling (Sondegaard et al., 2003; Holdren & Armstrong, 1980), sediment oxygen demand (Hatcher, 1986), macrophyte and benthic community distributions (Duarte & Kalff, 1986; Peeters et al., 2004) and other properties are all strongly dependent upon sediment properties, resuspension and distribution.

The distribution and resuspension of sediment within a lake basin are generally recognized to be a function of wind speed, fetch, water depth, basin slope, particle size, sediment cohesiveness and other factors (Hakanson, 1982; Lehman, 1975; Rowan et al., 1992; Bloesch, 1995). A number of studies have quantified the lake area subject to erosion and/or deposition and yielded simple predictive models using common morphometric parameters (Hakanson, 1982; Rowan et al., 1992; Blais & Kalff, 1995). Using effective fetch, exposure, or lake surface area as surrogates for wave energy and related parameters, these studies provide a means to delineate the critical depths that separate zones of erosion (i.e., the zone of regular resuspension and no significant net sediment deposition), transportation (where sediment accumulation is interrupted by infrequent periods of resuspension) and accumulation (where no resuspension or further focusing occurs) (Hakanson & Jansson, 1983; Blais & Kalff, 1995).

In a recent study, Anderson et al. (in review) evaluated a series of models and compared predicted sediment distributions with that found in the Salton Sea. The dynamic ratio model of Hakanson (1982) was found to reasonably estimate the area of erosion+transportation (aE+T) and therefore also the area of sediment accumulation with the equation:

$$a_{E+T} = 100 - a_A = 25\frac{\sqrt{a}}{\overline{D}}41^{0.061\overline{D}\,/\,\sqrt{a}} \qquad [1]$$

where a is the lake area and $\overline{D}$ is the mean depth. The critical depth and the distribution of the accumulation zone within a lake can, in turn, be determined using hypsographic data (Hakanson & Jansson, 1983). The model of Hakanson (1982) predicted sediment accumulation in the north basin, in good agreement with observed organic C distribution that exceeded 10% (dry-weight basis) there (Fig. 1). By contrast, organic C concentrations rarely exceeded 5% in the south basin (Fig. 1).

The original model of Hakanson (1982), however, does not allow one to delineate the critical depth that separates the erosional zone (zone of regular resuspension) from the transportational zone (zone of infrequent resuspension), zt, although empirical data from the Sea suggests that the critical depth is approximately 0.6x that of za (i.e., zt ≈ 0.6za).

In related studies, sediment resuspension has been reasonably predicted with relationships that use wind speed, wind direction, fetch and depth to sediment to infer loci and extent of resuspension (e.g., Carper & Bachmann, 1984). It has

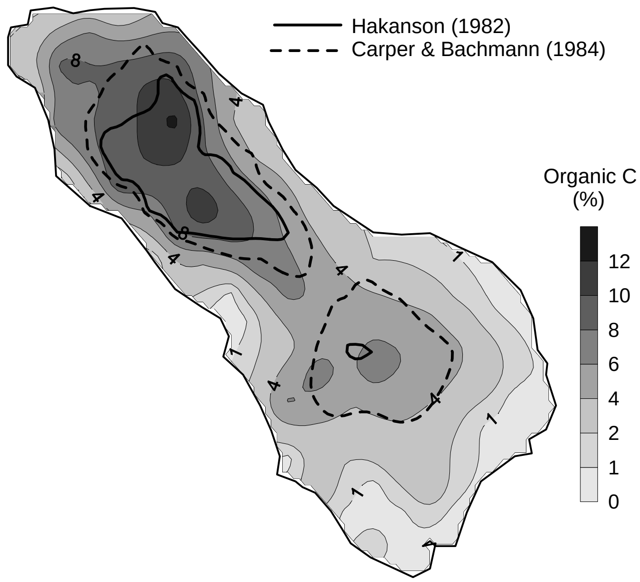

Figure 1.—Predicted zones of sediment accumulation within the Salton Sea.

been shown that resuspension and erosion of fine-textured bottom sediment occurs when deep-water waves enter water shallower than one-half the wavelength (Bloesch, 1995). The wavelength, L, of a deepwater wave is related to its period, T, by the relation:

$$L = \frac{gT^2}{2\pi} \qquad [2]$$

where g is the gravitational constant (Martin & McCutcheon, 1999). A wave's period can be estimated using the empirical equation developed by the US Army Coastal Engineering Research Center (Carper & Bachmann, 1984) that states:

$$T = \frac{2.4\pi U \tanh\left[0.077\left(\frac{gF}{U^2}\right)^{0.25}\right]}{g} \qquad [3]$$

where U is the wind speed and F is the fetch. In addition to allowing predictions about areas of resuspension within a lake, wave theory has been directly used to predict the sediment distribution pattern in Lake Ontario (Gilbert, 1999).

Although this model is more complex than that of Hakanson (1982), it did not as reasonably predict the zone(s) of organic matter accumulation within the Sea (Fig. 1), and rather predicted significant accumulation within southern basin of the Sea that was not found. Nevertheless, its explicit linking of meteorological conditions with a corresponding depth of resuspension make it potentially useful for making predictions about frequency of mixing/resuspension.

The dynamic ratio model of Hakanson (1982) was used to compare the relative distribution of the erosional, transportational and depositional zones within the different alternatives, while wave-theory calculations provide some predictions about the frequency and extent of sediment resuspension.

Dynamic Ratio Model (Hakanson, 1982)

The surface areas and maximum depths (Zmax) for the different alternatives were taken from the Alternative Modeling Results from the Value Planning Study (USBR). Volumes (not shown) and mean depths (Zmean) were estimated from hypsographic curves for the Sea (Table 1). Mean depths and surface areas were then inputted into the dynamic ratio model (eq. 1) to predict the percent area subject to erosion+transportation for each of the alternatives (at both 5 and 95% values, as described in the USBR study) (Table 1). For comparison, the properties of the current Sea have been included.

Table 1.—Predicted areas of erosion, transportation and accumulation for the proposed alternatives. Lower and upper values represent 5 and 95% levels from flow modeling.

			Area (%)		
Alternative	Area (km2)	Zmax (m)	Erosion	Transportation	Accumulation
Current Sea	973	15.2	43.2	44.7	12.1
NL-D	360 – 376	10.7 – 12.2	28.2 – 30.1	36.1 – 42.5	27.4 - 35.7
SL-D	429 – 453	12.2 – 13.7	26.4 – 34.1	37.8 - 39.0	28.1 – 34.6
SSA	340 – 413	11.6 – 13.7	33.3 – 37.5	28.3 - 30.8	34.2 – 35.9
NL-B	344 – 397	7.6 – 9.1	53.9 – 54.3	40.4 - >45.7	0 – 5.7
SL-B	328 – 376	7 – 8.5	nd[1] - 36.3	nd - 59.2	0 – 4.5
SL-B+Pond	324 – 364	6.7 – 8.2	nd – 44.3	nd – 50.2	0 – 5.5
EV Sea	546 – 700	4.6 – 8.2	nd*	nd	0
N Sea	518 – 660	4 – 7.3	nd	nd	0
No Project	563 – 712	4.9 – 8.5	nd	nd	0

[1] nd – areas of erosion and transportation are calculated from that estimated for accumulation, so it was not possible to independently predict these values for the alternatives where no areas of accumulation were predicted.

The proposed alternatives that involve construction of a north marine lake (e.g., NL-D and SSA alternatives) generally averaged around 370 km2, or approximately 38% of the surface area of the present Sea, while the south marine lake was slightly larger on average (324 - 453 km2). Other alternatives (e.g., the evoloving Sea and no project alternatives) were forecast to be larger (~550 - 700 km2). Maximum depths varied from 4 – 13.7 m, and are thus slightly to substantially shallower than the present Sea (Table 1). Mean depths were also lower to substantially lower than that for the present Sea (1.7 – 9.0 m vs. 9.5 m).

Application of Hakanson's model (Hakanson, 1982) indicates that about two-thirds of the surface area of the marine lakes in the North Lake-Dam, South Lake-Dam and SSA alternatives will be subject to periodic resuspension (i.e., erosion and/or transportation) and 27-36% will serve as depositional zones. Thus, the dynamic ratio model predicts that these alternatives will be less sensitive to wind-driven resuspension events when compared with the current Sea, where 87.9% of the bottom surface area of the Sea is predicted to be subject to at least occasional sediment resuspension. About 30% of the sediment surfaces for these alternatives are prone to erosion (regular resuspension) and generally slightly higher percentages of the sediment surfaces are predicted to be resuspended at least occasionally. The other alternatives, which tended to be shallower than the North Lake-Dam, South Lake-Dam and SSA alternatives, were predicted to be much more prone to sediment resuspension (Table 1). In fact, under the minimum elevation conditions, virtually all (100%) of the sediments within these basins were predicted to lie within the erosional and/or transportational zones (i.e., 0% accumulation) (Table 1). Critical depths that delineate the zone of accumulation from those of erosion and transportation varied depending upon the alternative, but were generally within 2 m of the maximum depth (or greater than the maximum depth for those alternatives with 0% accumulation area).

The predicted differences in sediment distribution and potential for resuspension within these alternatives are expected to have impacts on their thermal structure, water quality and trophic state. First of all, those configurations with large surface areas and small maximum depths (i.e., the EV Sea, N Sea and No Project alternatives), should remain well-mixed throughout the year. These basins will be subject to large wind energy inputs, so no region within these basins would be immune to periodic resuspension. Thus, potentially high levels of nonalgal turbidity may be present in these lakes, resulting in possible light-limitations to algal productivity. At the same time, regular resuspension will also enhance delivery of particulate and dissolved nutrients to the water column, increase oxygen demand, and without a true depositional zone, these alternatives may also not be as effective at burying Se and other contaminants.

At the opposite end of the spectrum, the deeper and smaller basins (e.g., NL-D, SL-D and SSA alternatives) will have a lower energy input per unit volume, with mixing extending down, at least occasionally, to about 10 m or so. This should also be about the maximum depth of the thermocline, so these alternatives are expected to have a hypolimnion that may persist for a greater length of time than found in the present Sea since the smaller fetch of these basins will reduce upwelling and internal seiching. These alternatives have a larger relative area for accumulation and thus will also have lower amounts of resuspension. Reduced resuspension will lower the amount of phosphorus, NH_3, and H_2S released to the epilimnion or the mixed portion of the water column, reduce nonalgal turbidity, lower oxygen consumption, and enhance Se reduction and burial. The incomplete mixing of the water column in these deeper impoundments indicates more extensive stratification, however, so increased accumulation of nutrients and H_2S within the hypolimnia is likely. Thus, upon fall turnover and mixing, very low DO concentrations and high H_2S and NH_3 concentrations may be present throughout the water column in these deeper alternatives. This may result in widespread fish kills and related ecological problems, as well as strong odor production, each fall.

Neither of these 2 conditions is especially attractive, although the deeper alternatives have greater potential for large fish kills and strong odors. The shallower alternatives will, through more frequent mixing of the entire water column, generally have higher levels of DO and lower concentrations of NH_3 and H_2S, although anoxia at the sediment-water interface is still likely.

Wave-Theory (Carper and Bachmann, 1984)

Solution to the wave theory equations (Carper & Bachmann, 1984) (eqs. 2 – 3) require meteorological information; wind data for 2001 were taken from the California Irrigation Management Information System (CIMIS) meteorological station #127, located on the western shore of the Salton Sea. Winds out of the NNW (essentially down the long axis of the lake) occurred about 10% of the time, although winds from the SE also occurred with some regularity (Fig. 2a). Wind speeds averaged 2.6 m/s, although periods of higher wind speeds, often >8 m/s, were also witnessed with some frequency (Fig. 2a). The maximum average hourly wind speed for the station was 10.9 m/s during 2001. Since wave periods, and therefore also wave lengths and wave-mixed layer depths, are related to wind speed (eqs. 2 – 3), we can expect that mixing to significant depths occurs regularly at the Salton Sea. The wind speeds were then sorted and ranked to determine exceedance probabilities for hourly average wind speeds. Thus, the median (50% exceedance probability) hourly wind speed at CIMIS Station #127 was 2.3 m/s, while 10% of the winds exceeded 4.3 m/s, and 1% exceeded 7.3 m/s (Fig. 2b).

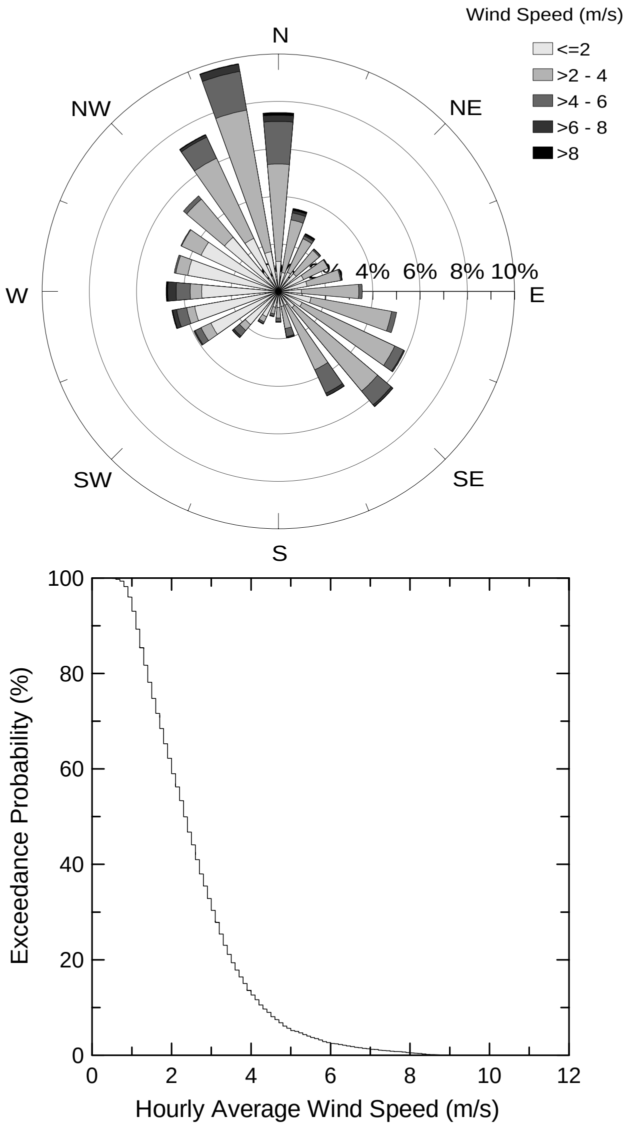

Figure 2.—Wind data from CIMIS station #127 (2001): a) wind rose showing hourly average wind speeds and directions, and b) wind speed exceedance probabilities.

Since the relative frequency of varying wind speeds can be extracted from meteorological records (Fig. 2b), it is informative to use this data to also calculate the relative frequency of mixing and resuspension. These wind speeds were used to calculate the wave periods (eq 3), wavelengths (eq 2), and critical depths (taken as ½ the wavelength) as a function of fetch. The average fetch lengths for the different alternatives were calculated from their surface areas assuming the basin shapes were approximately circular.

Solution to eqs. 2–3 using available wind speed data (Fig. 2b) allows one to predict the probability of resuspending bottom sediment as a function of fetch length (Fig. 3). The wave-mixed depth increased non-linearly with increasing fetch at any given probability. For example, windspeeds of 5.1 m/s occurred 5% of the time at the Sea; the wave-mixed depth increased from 1.28 m for a 1 km fetch to 5.3 m for a 10 km fetch and to 8.8 m at 35 km (the average fetch of the present Sea) (Fig. 3). Higher wind speeds that occurred at lower frequencies resulted in correspondingly larger resuspension depths (e.g., 7.3 m/s hourly average winds present 1% of the time were predicted to resuspend bottom sediments to 7.1 m for the NL-D alternative).

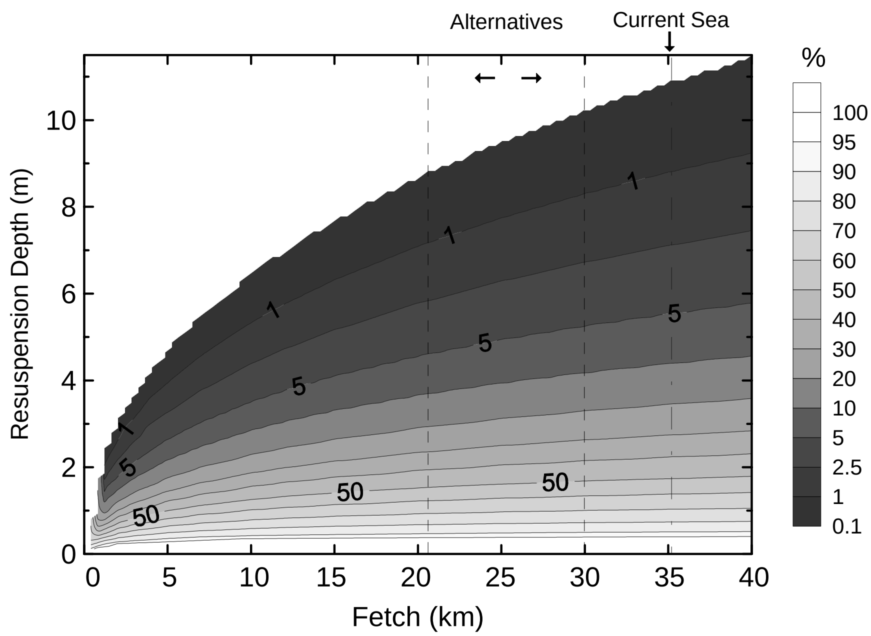

Figure 3.—Probability of sediment resuspension as a function of depth and fetch.

The evolving Sea and other larger surface area alternatives (with longer average fetch) was predicted to mix to >8 m depth at least 1% of the time. Since the maximum depth of, e.g., the evolving Sea was 4.6 – 8.2 m, this indicates that the entire sediment area of the evolving Sea with be regularly mixed at least 1% of the time (and possibly as frequently as about 7% of the time) (Fig. 3). Hence, no area of the evolving Sea would be protected against resuspension, consistent with the predictions of the dynamic ratio model (i.e., aA of 0%, Table 1).

Implications of These Findings

Both sets of model predictions (Hakanson, 1982; Carper and Bachmann, 1984) underscore the importance of wind-driven mixing and sediment resuspension in the very large and relatively shallow Salton Sea. This process is thought to strongly affect the functioning of the present Sea, and will affect the different proposed alternatives to varying degrees. Smaller deeper alternatives have the benefit of a larger area of accumulation and a lower areally or volume-weighted region of erosion and transportation, so that nonalgal turbidity will be lower than in shallower alternatives. Internal particulate and dissolved nutrient loading to the mixed (epilimnetic) part of the water column will also be lower so, other factors being held constant, one would expect better water quality than in the shallower alternatives. More efficient burial and reduction of Se would also be expected within these smaller, deeper alternatives. As noted above, however, the inability of wind to completely mix the water column in these proposed impoundments indicates that stratification may persist throughout the summer that will likely lead to very high levels of H_2S and NH_3 in the hypolimnion that will be released to the entire water column upon fall mixing. Somewhat shallower polymictic basins may be more desirable since they may still be able to sequester Se by maintaining anaerobic conditions at the sediment-water interface without large NH_3 and H_2S accumulation in the lower water column.

References

Anderson, M.A., L. Whiteaker, E. Wakefield and C. Amrhein. (in review). Properties and distribution of sediment in the Salton Sea, California. Submitted to Hydrobiologia. 35 manuscript pages.

Blais, J.M. & J. Kalff, 1995. The influence of lake morphometry on sediment focusing. Limnology and Oceanography 40: 582-588.

Bloesch, J., 1995. Mechanisms, measurement and importance of sediment resuspension in lakes. Marine and Freshwater Research 46 :295-304.

Carper, G.L. & R.W. Bachmann, 1984. Wind resuspension of sediments in a prairie lake. Canadian Journal of Fisheries and Aquatic Sciences 41: 1763-1767.

California Irrigation Management Information System (CIMIS). 2004. California Dept. of Water Resources. www.cimis.water.gov.

Duarte, C.M. & J. Kalff, 1986. Littoral slope as a predictor of the maximum biomass of submerged macrophyte communities. Limnology and Oceanography 31: 1072-1080.

Gilbert, R., 1999. Calculated wave base in relation to the observed patterns of sediment distribution in northeastern Lake Ontario. Journal of Great Lakes Research 25: 883-891.

Hakanson, L., 1982. Lake bottom dynamics and morphometry: the dynamic ratio. Water Resources Research. 18: 1444-1450.

Hakanson, L. & M. Jansson. 1983. Principles of Lake Sedimentology. Springer-Verlag, New York, NY.

Hatcher, K.J. 1986. Sediment Oxygen Demand: Processes, Modeling & Measurement. Institute of Natural Resources, Univ. of Georgia, Athens, GA.

Holdren, G.C. & D.E. Armstrong, 1980. Factors affecting phosphorus release from intact lake sediment cores. Environmental Science and Technology. 14: 79-87.

Lehman, J.T., 1975. Reconstructing the rate of accumulation of lake sediment: the effect of sediment focusing. Quaternary Research 5: 541-550.

Martin, J.L. & S.C. McCutcheon, 1999. Hydrodynamics and Transport for Water Quality Modeling. Lewis Publ., Boca Raton, FL. 794 pp.

Peeters, E.T.H.M., R. Gylstra & J.H. Vos, 2004. Benthic macroinvertebrate community structure in relation to food and environmental variables. Hydrobiologia 519: 103-115.

Rowan, D.J., J. Kalff & J.B. Rasmussen, 1992. Profundal sediment organic content and physical character do not reflect lake trophic status, but rather reflect inorganic sedimentation and exposure. Canadian Journal of Fisheries and Aquatic Sciences 49: 1431-1438.

Rowan, D.J., J. Kalff & J.B. Rasmussen, 1992. Estimating the mud deposition boundary depth in lakes from wave theory. Canadian Journal of Fisheries and Aquatic Sciences 49: 2490-2497.

Sondegaard, M., J.P. Jensen & E. Jeppesen, 2003. Role of sediment and internal loading in shallow lakes. Hydrobiologia 506-509: 135-145.