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Ecological Modelling 128 (2000) 101–125

ECOLOGICAL MODELLING

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Modelling the impact of water level fluctuations on water quality (suspended particulate matter) in Lake Kinneret, Israel

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Received 22 June 1999; received in revised form 24 September 1999; accepted 19 October 1999

Abstract

A dynamic (time dependent) mathematical model of the monthly cycling of suspended particulate matter (SPM) in lakes with variable water levels has been developed. The model has been applied for the large subtropical Lake Kinneret (Israel), which has variable water levels related to domestic freshwater needs and climatological conditions. The main conclusions from this work are: 1. Uncertainty analyses (Monte Carlo simulations) have shown that the two most important model uncertainties concern sedimentation and erosion related to a lowering of the wave base (= the water depth separating areas where discontinuous and continuous sedimentation of fine matter occurs). The best way to improve the reliability of the mean monthly SPM-predictions would be to improve the modelling parts related to sedimentation and a lowering of the wave base. All other processes are of less importance for the SPM-predictions (e.g. inflow, outflow, primary production, resuspension, mineralization and mixing). 2. A successive, gradual lowering of the wave base seems to correspond to the 'worst case' scenario likely to alter SPM-values the most. 3. In the 'worst case' scenario, very high levels of SPM may be maintained for a long time (> 10 years), which would likely cause serious changes to the Lake Kinneret ecosystem. These results indicate the existence of a narrow threshold range of artificial changes of lake morphometry (water level lowering of about 4–5 m from the maximum water level), which may cause significant deterioration of water quality in Lake Kinneret.

Keywords: Suspended particulate matter; Lake water quality; Lake management; Mathematical lake model; Lake Kinneret; Monte Carlo simulations

1. Introduction

Suspended particulate matter (SPM) plays a fundamental role in aquatic systems. For example, SPM regulates the two major transport routes, the dissolved pelagic route and the partic-

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0304-3800/00/$ - see front matter
PII: S0304-3800(00)00200-3

ulate sedimentation and benthic route, of all types of materials and contaminants in aquatic ecosystems. The fraction of any given substance in dissolved phase (D) and the fraction in particulate phase ($P = 1 - D$) are directly related to the concentration of SPM in the water (Håkanson, 1999). SPM in the water column is also a metabolically active component of aquatic ecosystems. The carbon content of SPM is crucial at lower trophic levels as a source of energy for bacteria, phytoplankton and zooplankton (Wetzel, 1983; Jørgensen and Johnsen, 1989). SPM is also important at higher hierarchical levels, combining biotic communities and substrates, where SPM influences many tropho-metabolic properties (Khailov, 1974; Ostapenia 1989). Finally, SPM is directly related to many variables of general use in lake management as indicators of water clarity (e.g. Secchi depth and water transparency). These variables are important regulators of primary production, which in turn regulates secondary production (e.g. fish production). Hence, the effects of SPM on recycling processes of organic matter, major nutrients and pollutants determine the ecological significance of SPM in any given aquatic environment.

Understanding the physical mechanisms that control the distribution of suspended particles in lakes is an issue of both theoretical and applied concern, as physical processes ultimately shape aquatic ecosystems (Håkanson and Peters, 1995). Physical processes, from large-scale circulations to small-scale turbulence, generally determine the spatial distribution of biological and chemical components in a given aquatic ecosystem (Reynolds, 1978). In water bodies where the organic material is predominantly autochthonous, the nutrient pool in the epilimnion depends on the balance between sedimentation losses and upward nutrient fluxes from the hypolimnion (Carpenter et al., 1986). The release of nutrients from the sediments and the subsequent transport upward directly affect the production of authocthonous particles and the trophic status of such lakes (Vollenweider, 1968; Canfield and Bachmann, 1981; Marsden, 1989). In Lake Kinneret the turbulent benthic boundary layers (TBBL) generated by internal wave and bottom interactions is important for the vertical transport of nutrients and SPM. This mechanism is often more effective than the transport directly through the thermocline (Munnich et al., 1992; Imberger, 1994, 1995; Ostrovsky and Yacobi, in press). The turbulent properties and thickness of the TBBL vary with time and space (Imberger, ongoing research). Spatial variations of turbulent mixing can cause significant spatial heterogeneity in the distribution of nutrients (Gargett, 1997). The extensive microstructure profiling in Lake Kinneret (Imberger, ongoing research) has shown the complex turbulent structure within the thermocline and hypolimnion in Lake Kinneret. Spatial variability in the near-bottom shear stress can result in localised resuspension of sediments from the bottom. The significance of seiche activity for sediment resuspension from the bottom has been determined for lakes of moderate depths (Chambers and Eadie, 1981; Gloor et al., 1994; Weyhenmeyer, 1996). In the relatively deep Lake Kinneret, the internal seiches apparently cause resuspension from the area where metalimnetic isotherms cross the bottom (Ostrovsky et al., 1996). Thus, one can expect that the spatial heterogeneity in biochemical and sedimentological processes could be related with the turbulent 'climate' in the lake.

From this, it is evident that SPM in lakes can emanate from various primary (inflow and production) and secondary (resuspension) sources and that there are crucial 'scale' problems to all processes and mechanisms regulating SPM in lakes. This work will present a dynamic model for Lake Kinneret based on ordinary differential equations. The basic structure of all models depends on the target variable(s) to be predicted, which for this model is mean monthly concentrations of SPM in surface and bottom water. The rationale for this scale of modelling in this context is that it is generally more difficult to model at fines time scales and to account for more compartments (like metalimnion and TBBL) and that more extensive models require more driving variables, which would be more difficult to access. Calibrations and validations of big models tend to be very costly. In practical contexts of lake management, one would not be interested in predicting site-specific conditions in the 'sampling bottle' but rather to predict mean conditions over larger areas and time intervals, like mean monthly values for SPM for the entire epilimnion.

Lake Kinneret is the most important resource of freshwater to Israel (Serruya, 1978). Great efforts are taken to maintain and improve water quality of the lake since this is crucial for agriculture, drinking water, urban water supplies, etc. During recent years there has been less rain than the long-term average and increasing demands for water. This means that there are strong political, social and economical reasons to try to predict realistic ecological consequences related to a further lowering of the water level of Lake Kinneret below the present lowest permissible level (Hambright et al., 1997). The basic questions addressed in this paper are: how would water level changes in Lake Kinneret influence the water quality expressed as changes in concentrations of suspended particulate matter? More generally, how would different patterns in water level fluctuations influence SPM in the lake? Is there a 'worst case scenario' which should be identified so that it could be avoided? These are basic questions of great importance also for other lakes and reservoirs in the world.

These questions are addressed here using a dynamic (= time dependent) model for SPM, which is meant to account for all relevant major processes and factors regulating SPM. The model is based on components described in Håkanson and Peters (1995) and Håkanson (1999), but there are several empirical simplifications in the model applied to Lake Kinneret.

2. A brief description of Lake Kinneret

Lake Kinneret is a warm monomictic lake with a surface area of 170 km^2 (maximum area) and average and maximum depths of 26 and 42 m, respectively. The lake is typically stratified between April and December and full homothermy occurs usually during January–March (Hambright et al., 1994). The Jordan River is the major inflow, accounting for about 70% of the total annual inflow to the lake. Since maxima in water input (January–March) and exploitation (July–September) occur in different seasons, the lake altitude fluctuates between -209 (corresponding to water level lowering, $WL = 0$, in the following simulations) and -213 m ($WL = 4$). Seiches are present during the entire stratified period, as a response to the daily westerly winds generally blowing in the afternoon. Seiche amplitudes of up to 10 m with periods of ca. 24 h are common (Serruya, 1975). Further background on Lake Kinneret may be found in Serruya (1978).

The difference between the chemical composition of the hypolimnion and the epilimnion is great (Serruya, 1978; Berman et al., 1992; Eckert and Hambright, 1996). During the stratified period, the epilimnion retains high concentrations of oxygen, but is depleted in N and P. The hypolimnion is devoid of O_2 and contains high concentrations of H_2S (up to 10 mg/l). The concentrations of ammonia and soluble reactive phosphorous (SRP) in the epilimnion are barely above the limits of the analytical detection methods; concentrations of those substances in the anoxic hypolimnion are in the range from 0.3 to 1.5 mg/l, and from 0.002 to 0.150 mg/l, respectively. The accessible P and N in the epilimnion control and limit the phytoplankton biomass and production (Scharf et al., 1986; Pollingher et al., 1988; Berman et al., 1995). Relatively stable values of total-P and algae biomass (93–116 mg chlorophyll/m^2) prevail in the photic zone during the summer–fall months (Berman et al., 1992) when sedimentation rates are relatively high (Serruya, 1977; Klein and Koren, 1998) and the external nutrient supply small. This suggests intense nutrient recycling by, e.g. seiche-induced entrainment of hypolimnetic waters. A gradual destratification during fall gives substantial sources of dissolved nutrients to the epilimnion (Yacobi et al., 1991; Nishri and Koren, 1993; Ostrovsky and Yacobi, in press).

3. The dynamic SPM-model used for Lake Kinneret

An outline of the model is given in Fig. 1. All equations are compiled in Table 1 and the model variables are given in Table 2. To provide an initial illustration of the model and its use, Table 3 gives a compilation of all fluxes in a situation where the water level has been lowered gradually 2 m in 1 year (2/12 m/month). One can then note that sedimentation on accumulation areas (A-areas, see later for definition; SedA in tons of SPM in dry weight (dw) per month) is the dominating process under these conditions and that the outflow is the lowest flux. From a mass-balance perspective, and for the following uncertainty analyses, this is very important information because errors and uncertainties for large fluxes are more serious than for small fluxes in predicting SPM-values. So, the ranking of the fluxes given in Table 3 also indicates the relative importance of the given processes (under the given conditions and for this lake). For more information about SPM-fluxes and processes in Lake Kinneret based on field measurements, see Parparov and Berman (1999).

The model accounts for the following processes regulating the SPM-fluxes to, from and within the lake.

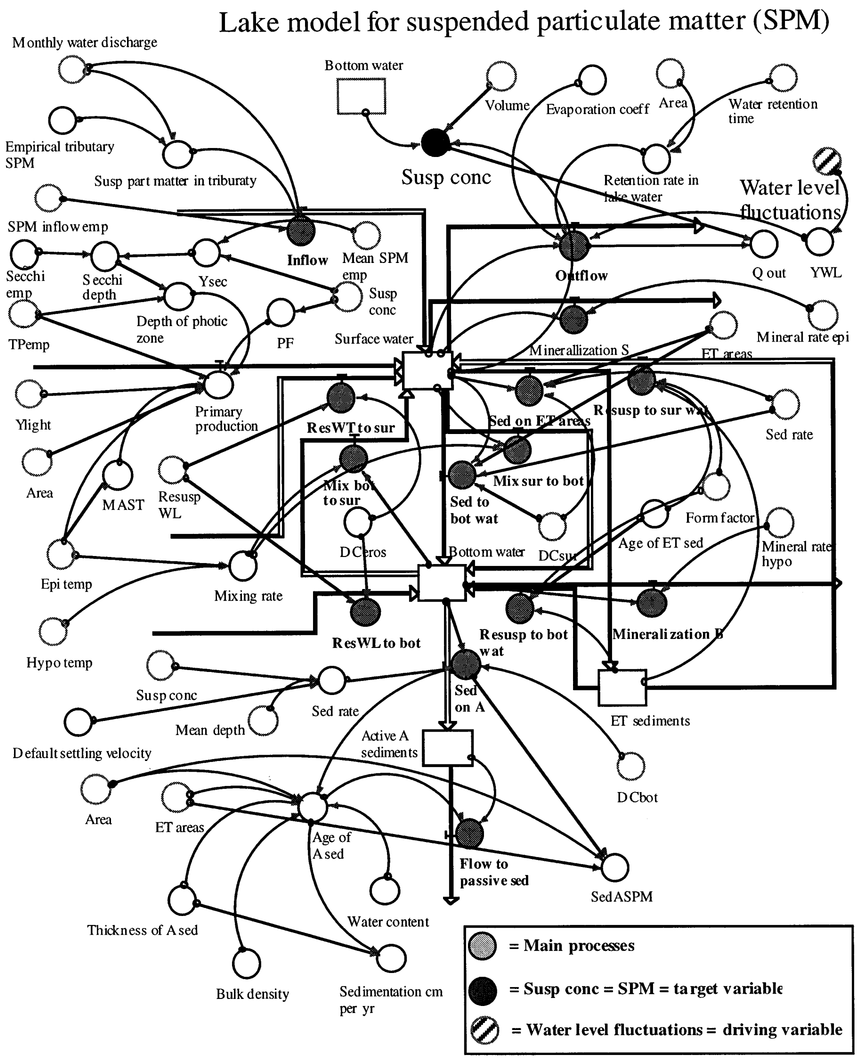

Fig. 1. An outline of the lake model for SPM.

Table 1
A compilation of the differential equations making up this model for SPM

Box 1. Active A-sediments. All fluxes are given in tons dw/month. A is the amount (tons dw) in active A-sediments
$A(t) = A(t - \mathrm{d}t) + (\mathrm{SedA} - \mathrm{FromA})^*\mathrm{d}t$
SedA = sedimentation on A
SedA = B*KT*(1 − DCbot) + B*KT*2*DCbot
FromA = Flow to passive A-sediments
FromA = A/AgeA
AgeA = DA*Area*(1 − ET)*10000*(1 − W/100)*d/(SedA*10^6)
KT = sedimentation rate (1/month)
DCbot = distribution coefficient for the resuspended fraction to bottom water
DA = depth of active sediments (0.05 m)
ET = ET-areas (a distribution coefficient; ET = 1 means that 100% of the lake bottom is dominated by process of fine sediment erosion and transport)

Box 2. Erosion related to a lowering of the wave base. AWL is the amount available for erosion (tons dw)
AWL(t) = AWL(t − dt) + (ERin − ResuspWL)*dt
ERin = if (WL − DELAY(WL,1)) > 0 then ERin = EROS else ERin = 0
ResuspWL = AWL*ER

Box 3. Bottom water. B is the amount of SPM in bottom water (tons dw)
$B(t) = B(t - \mathrm{d}t)$ + (SedB + ResETB + MixSB + ResWLB − MixBS − SedA − MinB)*dt
SedB = S*KT*(1 − ET)*(1 − DCsur) + S*KT*2*(1 − ET)*Dcsur
ResETB = ET*(1/AgeET)*(Vd/3)
MixSB = S*MixR
ResWLB = ResuspWL*(1 − DCeros)
MixBS = B*MixR
SedA = B*KT*(1 − DCbot) + B*KT*2*Dcbot
MinB = B*MinRhypo
DCsur = distribution coefficient for the resuspended fraction to surface water

Box 4. Areas of erosion (E) and transport (T)
ET(t) = ET(t − dt) + (SedET − ResETB − ResETS)*dt
SedET = S*KT*ET*(1 − DCsur) + Su*KT*2*ET*Dcsur
ResETB = ET*(1/AgeET)*(Vd/3)
ResETS = (ET/AgeET)*(1 − Vd/3)
AgeET = 12/1.386

Box 5. Surface water
$S(t) = S(t - \mathrm{d}t)$ + (In + MixBS + ResERS + PP + ResWTS − Out − SedB − SedET − MixSB − MinS)*dt
In = Q*Cin; the tributary inflow of SPM in tons dw/month.
MixBS = B*MixR
ResETS = (ET/AgeET)*(1 − Vd/3)
PP = Y^*_{light} ((1 − PF)/0.5)*(TPemp*10 − 79)*0.001*30*(1/0.45)*Area*Dz*(EpiT/(MAST))*10^{-6}
Y_{light} = Mean monthly daylight/Mean annual daylight
PF = Particulate fraction of total phosphorus
Dz = Depth of photic zone
EpiT = Eplimnetic mean monthly temperatures (empirical values)
MAST = Mean annual surface water (= epilimnetic) temperature
TPemp = Empirical mean monthly values of total phosphorus in Lake Kinneret
ResWTS = ResuspWL*Dceros
Out = S*RR*Y^*_{WL} EC; this is the lake outflow of SPM. Values in tons dw/month.
SedB = S*Sed_rate*(1 − ET)*(1 − DCsur) + S*KT*2*(1 − ET)*DCsur
SedET = S*KT*ET*(1 − DCsur) + S*KT*2*ET*Dcsur
MixSB = S*MixR
MinS = S*MinRepi

3.1. Inflow

In this model, the inflow of SPM via the Jordan River (*In*) is given by empirical data of mean monthly SPM-values (Table 4). Generally, in models of this kind the inflow is given by Q*Cin, where Q is the mean monthly water discharge in m^3/month and Cin is the riverine concentration of SPM (g dw/m^3).

3.2. Primary production (PP)

Empirical PP-data are available from 1992 to 1996 (Table 5). The model has been calibrated to yield data corresponding to these mean empirical values when the lake is full of water ($WL = 0$, related to the maximum lake area of 170 km^2). The good correspondence between the modelled values and the mean empirical data is shown in Fig. 2. This simulation gives modelled values for $WL = 0$ for the first 60 months and then the water level has been lowered 2 m for the next 60 months ($WL = 2$). One can note that this will not reduce PP in any significant manner.

Table 2
A compilation of data used in these calculations

Annual precipitation = 408 mm/year
Area max = 170*10^6 m^2
Bulk_density = 1.1 g ww/cm^3.
Catchment area = OA + (2560)*10^6 in m^2; OA is the area added to the catchment when the water level is lowered.
Evaporation coeff. (EC) = 0.1; the evaporation from the lake water is assume to lower the water discharge from the lake by 90% relative to the water inflow to the lake. This value is derived from calibrations using empirical data for water outflow from the lake.
Max. depth = 42.0 − WL; the maximum depth in m.
Mean depth max = 26 m.
Mineral_rate_epi (MinRepi) = MinR*(EpiT/4); the mineralization rate is assumed to be directly proportional to the temperature: the higher the epilimnetic temperature the greater the mineralization.
Mineral_rate_hypo MinRhypo) = MinR*(HypoT/4)
Mineralization_rate (MinR) = 0.05 (1/month)
OA = Area_max − Area; this is the area (m^2) above the water level when the water level is lowered from the maximum value. OA is then included in the catchment area.
Thickness_of_A_sed (DA) = 5 cm; from Håkanson and Jansson (1983) it is assumed that the depth of the biologically active sediments may be set to about 5 cm.
Water content = 80%; this is a default value (Håkanson and Jansson, 1983) of the water content of the active (0–5 cm) sediments in lakes; values in % ww.

The mean monthly primary production of the lake is basically calculated from an equation (yielding PP in g C/m^2*day) given by Peters (1986):

$$PP = Y^{*}_{light}\ ((1 - PF)/0.5)^{*}(TP^{*}10 - 79) \\ {}^{*}0.001^{*}30^{*}(1/0.45) \\ {}^{*}Area^{*}Dz^{*}(EpiT/(MAET))^{*}10^{-6} \qquad (1)$$

This equation has been modified by: (1) a temperature moderator, which gives the ratio between mean monthly (empirical) surface water temperatures and mean annual surface water temperature (°C); the higher the surface water temperatures, the higher the PP-value; (2) a light moderator (Y_{light}) given by the ratio between the mean number of hours with daylight per month and the mean annual value for the number of monthly hours with daylight (10.03; the greater the number of hours with daylight, the higher the PP-value; Table 4); and (3) a moderator for the dissolved fraction of phosphorus, which by definition is the fraction of phosphorus that should influence the primary production. The primary production is calculated for the volume of the photic zone using information on lake area (which changes with water level). The PP values are given in tons dw/month. The factor 0.45 is a standard calculation factor (Håkanson and Peters, 1995) to alter g C into g dw.

PF is the particulate fraction of total phosphorus. This means that the dissolved fraction (DF) is equal to $1 - PF$. The figure 0.5 in Eq. (1) is a characteristic reference value for DF and the ratio between $(1 - DF)/0.5$ is, thus, a simple dimensionless moderator for how variations in PF influence PP. PF is calculated from Håkanson (1999) as a function of SPM as:

$$PF = -0.65/(1 + SPM) + 0.65 \qquad (2)$$

TP is the empirical mean monthly lake concentration of total phosphorus (Table 4). Area is the lake area in m^2. Variations in lake area related to water level fluctuations are handled by the sub-

Table 3
A comparison between all the fluxes (values in ktons/month) in the SPM-model related to a situation when the water level (WL) is lowered 2 m (from WL = 0) during 1 year[a]

Month	WL	SedA	Pass	SedB	PP	SedET	ErosS	ErosB	MixSB	MixBS	ResETB	In	MinS	ResETS	MinB	Out
1	0.17	21.4	16.7	17.9	16.5	4.4	0.0	0.0	8.2	7.4	3.1	4.7	1.54	1.9	1.4	0.16
2	0.33	20.0	15.7	17.2	14.8	4.2	0.1	0.1	8.0	7.0	3.0	7.4	1.47	1.8	1.2	0.16
3	0.50	18.2	14.4	15.0	14.6	3.7	0.2	0.2	7.3	6.7	3.0	3.4	1.49	1.8	1.2	0.14
4	0.67	20.1	16.0	18.1	21.7	4.5	0.5	0.5	1.9	1.6	2.9	2.5	1.90	1.8	1.2	0.15
5	0.84	21.1	16.9	18.4	21.2	4.5	0.9	0.9	1.0	0.9	2.9	1.2	2.25	1.8	1.3	0.14
6	1.00	21.4	17.2	18.2	21.1	4.5	1.5	1.5	0.7	0.6	2.9	0.9	2.57	1.8	1.3	0.13
7	1.17	24.1	19.5	20.6	24.5	5.1	2.4	2.4	0.6	0.6	2.9	0.6	2.88	1.8	1.4	0.13
8	1.33	28.0	22.9	23.5	27.2	5.8	3.6	3.6	0.6	0.6	3.0	0.5	3.12	1.8	1.5	0.14
9	1.50	30.5	25.1	24.2	25.7	6.0	5.0	5.0	0.6	0.6	3.0	0.6	3.04	1.8	1.6	0.13
10	1.67	32.3	26.8	24.2	23.1	6.0	6.9	6.9	0.7	0.8	3.1	0.9	2.70	1.9	1.6	0.12
11	1.84	36.7	30.7	26.8	22.9	6.7	9.1	9.1	1.1	1.2	3.2	2.1	2.35	1.9	1.7	0.11
12	2.00	42.0	35.4	30.3	18.2	7.6	11.7	11.7	8.8	9.7	3.3	7.7	1.98	2.0	1.8	0.11
Sum:		316	257	254	251	63	42	42	40	38	36	32	27	22	17	2
Rank:		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

[a] The ranking of these fluxes has been done based on the annual data (Sum). Abbreviations: ErosB, erosion from a lowering of the wave base to bottom water, ErosS, erosion from a lowering of the wave base to surface water; In, inflow; MinB, mineralization in bottom water; MixBS, mixing from bottom to surface water; MixSB, mixing from surface to bottom water; Out, outflow from Lake Kinneret; Pass, transport from active to passive sediments; ResETB, resuspension from ET-areas to bottom water; ResETS, resuspension from ET-areas to surface water; SedA, sedimentation on A-areas; SedB, sedimentation to bottom water.

Table 4
Empirical data on the mean monthly transport of suspended particulate matter in Jordan River from 1992 to 1997 and mean monthly empirical values for number of hours with daylight per month (Light), total-P concentrations in lake water (TP), EpiT, HypoT and MixR

Month	SPM (tons dw/month)	Light	TP (μg/l)	EpiT (°C)	HypoT (°C)	MixR (1/month)
January	4624	8.25	26	15.01	14.87	1
February	7427	8.84	23	14.70	14.21	1
March	3282	9.93	19	16.48	14.30	1
April	2531	11.25	22	18.71	14.31	0.23
May	1142	11.70	19	22.42	14.53	0.13
June	903	12.15	17	26.17	14.65	0.09
July	551	11.70	19	27.74	14.72	0.08
August	502	10.80	22	28.53	14.77	0.07
September	623	9.90	23	28.20	14.89	0.08
October	874	9.00	24	26.09	14.79	0.09
November	2120	8.55	29	22.21	14.86	0.14
December	7837	8.32	31	17.94	15.03	1

model for area, which will be discussed later on. EpiT is the mean monthly epilimnetic temperatures (°C), as given by empirical data from 1992 to 1998 (Table 4). MAET is the mean annual epilimnetic temperature (22.83°C). Dz is the depth of the photic zone in m. The depth of the photic zone has been calculated from the Secchi depth and the calculated SPM-concentration (the higher the SPM-value to lower the Secchi depth; Håkanson, 1999), accordingly:

$$Dz = 5*Sec*Y_{Sec} \quad (3)$$

For a typical Secchi depth in Lake Kinneret, 3.1 m (Berman, 1976), Eq. (3) gives Dz = 15 m (when $Y_{sec} = 1$). This corresponds to the characteristic value of Dz for Lake Kinneret (Berman et al., 1995). Changes in SPM will, however, also cause changes in Secchi depth, according to the following equation:

$$Y_{Sec} = 1 - 0.75*((SPM/3.4) - 1) \quad (4)$$

For example, if SPM changes by a factor of 2.4 (e.g. from 2.5 to 6 mg/l), then Secchi depth would decrease by a factor of 4 (from 8 to 2 m; Håkanson, 1999). The normal value for this moderator is put at the mean empirical value for Lake Kinneret (SPM = 3.4; Table 6).

3.3. Outflow

Empirical data on water discharge from the lake (Qout, see Table 7) have been used together with the modelled SPM-data get one measure of the lake outflow of SPM. The other alternative (which has been used here in simulations of water level changes where the available empirical data for Qout are not relevant) is calculated in the model accordingly:

Table 5
Empirical data on the mean monthly primary production in Lake Kinneret based on data from 1992 to 1996

Month	SPM (tons dw/month)
January	10 877
February	15 372
March	24 724
April	32 952
May	36 223
June	25 291
July	24 619
August	20 136
September	23 821
October	20 674
November	12 922
December	10 770

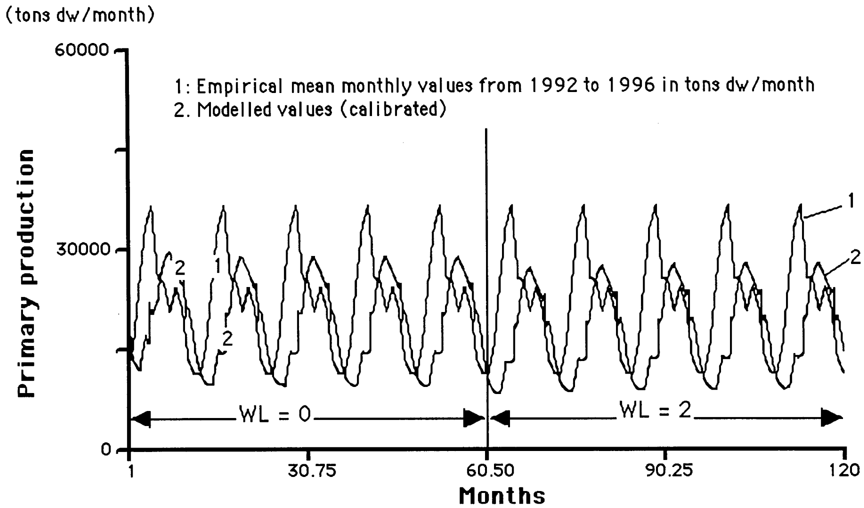

Fig. 2. A comparison between empirical data for primary production and modelled values when for 60 months the WL = 0 and then WL = 2 m (below the maximum water level) for 60 more months.

3.3.1. Step 1

For lakes larger than 0.2 km^2 with theoretical lake water retention times longer than 1 month, the theoretical water retention rate (RR in 1/month) is first given by (from Håkanson, 1999):

$$RR = 1.386/Tw^{((10/(Tw + 10 - 1) + 0.5)/1.5)} \quad (5)$$

where Tw, the theoretical lake water retention time in months (Tw = V/Qin).

The retention rate is generally set to $1/Tw^1$ in simple mass-balance calculations for polymictic lakes. For large, deep lakes with small drainage areas, i.e. lakes with a long theoretical water retention time (Tw), thermal and chemical stratifications, hydrological flow patterns and currents influence the retention time of water and SPM. In this model, we will use a function for the exponent in the expression $1/Tw^{exp}$. This exponent (exp) should be about 1 in polymictic lakes and it should decrease for stratified lakes with a long theoretical water retention. There are several ways to define such a formula (Håkanson and Peters, 1995). Here, the approach developed from studies of radiocesium is used (Eq. (5); Håkanson, 1999). This approach is meant to give better descriptions of the water retention processes and improve the predictive power of the model.

3.3.2. Step 2

The evaporation from the lake water is assumed to lower the water discharge from the lake by 90% relative to the water inflow to the lake. This value is derived from calibrations using empirical data for water outflow from the lake and Table 7 shows that this gives a good fit when the two approaches to calculate SPM outflow are compared. This means that the outflow of SPM from the lake is given by:

Table 6
Empirical data on SPM (mg/l) in Lake Kinneret 1992–1996

Month	1992	1993	1994	1995	1996	MV	S.D.
1	2.4	1.7	2.1	2.7	2.2	2.2	0.37
2	3.8	3.7	2.7	3.1	2.1	3.1	0.71
3	2.1	6.6	4.2	3.8	2.9	3.9	1.70
4	2.4	6.3	9.0	11.0	3.9	6.5	3.54
5	7.9	6.8	6.5	11.2	4.9	7.5	2.35
6	3.5	3.5	2.6	3.7	4.0	3.5	0.52
7	3.2	2.0	2.1	2.8	3.0	2.6	0.54
8	3.7	1.9	2.1	3.3	1.4	2.5	0.98
9	2.4	1.7	3.2	3.3	2.4	2.6	0.66
10	1.4	2.1	1.7	3.5	2.2	2.2	0.80
11	1.9	1.1	1.4	3.7	2.7	2.2	1.05
12	1.8	1.6	1.8	2.5	2.2	2.0	0.36
MV						3.4	1.13

Table 7
Empirical data on water flow from Lake Kinneret (mean monthly values in 10^6 m^3/month) based on data from 1993 and 1995, calculated data on SPM in the lake water, calculated outflow (Qout*SPM) and calculated outflow based on the calibrated model (for WL = 0)

Qout ((10 ^ 6)^3/month)	SPM (g dw/m^3)	Outflow (Qout*SPM) (tons dw/month)	Calculated outflow (tons dw/month)
72.7	3.5	257	164
75.6	3.4	259	166
36.8	3.2	117	154
35.9	3.4	123	173
42.8	3.5	148	172
46.4	3.4	159	167
48.9	3.6	176	176
47.1	3.8	180	184
47.8	3.9	184	180
44.1	3.8	166	172
32.1	3.9	124	178
33.5	4.0	133	183
Annual outflow		2026	2070

$$\text{Outflow} = S^*\text{RR}^*Y^*_{\text{WL}}\text{EC} \quad (6)$$

Where the outflow is given in tons dw/month. S is the SPM-amount in the surface water (tons dw); RR is given by Eq. (5); Y_{WL} is a dimensionless moderator describing how a lowering of the water level (WL in m) would reduce the outflow of SPM; and EC is the evaporation coefficient (= 0.1). The dimensionless moderator is meant to account for the fact that if the water level is lowered beyond a certain critical value, no water will flow out of the lake for topographical reasons. The critical limit has been set to WL = 6 m and Y_{WL} is then given by:

$$Y_{\text{WL}} = (1 - \text{WL}/6) \quad (7)$$

From Fig. 3 and Table 3, one can note that the outflow of SPM is the smallest of all the given fluxes.

3.4. Mineralization

In the model, mineralization means non-deposit net losses of SPM in the water mass related to respiration plus solubilization minus non-photosynthetic formation (see Parparov and Berman, 1999, for further information on these processes in Lake Kinneret). The value used for the mineralization rate (MinR = 0.05 per month; that is 5% of the total amount of SPM in the water mass is being mineralised each month) emanates from calibrations with the LEEDS-model (Håkanson, 1999). The mineralization rate operates in this model only on SPM in the epilimnetic and hypolimnetic compartments, and not in the sediment compartments (for ET-areas and A-areas), which would require including different (but largely unknown) mineralization rates for the sediment compartments. We account for the omission of mineralization in the sediment compartments by setting the resuspension rate for ET-areas high (the mean age of the ET-deposits is set low, to 12 months; Håkanson, 1999). The mineralization rate in the surface waters (MinS) is assumed to be directly proportional to water temperature, where:

$$\text{MinS} = \text{MinR}^*(\text{EpiT}/4) \quad (8)$$

where 4 (°C) is a general reference temperature (a typical value for hypolimentic temperatures during winter in stratified lakes). The radio Epi/4 is used here as a simple dimensionless moderator.

Fig. 3 gives a comparison between the given fluxes (MinS means mineralization in surface water) for four different WL-values, 0, 2, 4 and 6 m below the maximum level. One can note that primary production dominates among the given five fluxes when $0 < WL < 4$ and that the outflow is the smallest of the given fluxes. If the water level is lowered to 6 m below the maximum level, the model predicts major changes for, notably primary production. In the following, we will give several compilations of fluxes, and the results in Fig. 3 can be regarded as a reference.

3.5. Mixing

In this model, the surface water (epilimnion) and the bottom water (hypolimnion) are given by two compartments. The fluxes of SPM to, from and between these two compartments are handled by different processes and 'mixing' is the process transporting SPM between these two compartments. When the mixing rate (MixR in 1/month) is 1, the two compartments mix completely. MixR is defined by the difference between surface and bottom water temperatures in such a way that the value is 1 when the waters are homeothermal (the limit for this is set at a temperature difference of 4°C between mean monthly epilimnetic, EpiT, and hypolimnetic temperatures, HypoT, according to Håkanson, 1999) and smaller than 1 during stratified conditions when mixing of suspended particles between bottom and surface waters is lower.

$$\text{If}\quad 1/\text{ABS}(\text{EpiT}-\text{HypoT}) > 0.25 \quad \text{then MixR} = 1 \text{ else MixR} = 1/\text{ABS}(\text{EpiT}-\text{HypoT}) \qquad (9)$$

The empirical data used for HypoT emanate from 1992 to 1998. The data are given in Table 4 together with calculated values for MixR.

From this information, one can note that according to this model, the lake is stratified from April to November, which is in good agreement with existing knowledge. The fluxes related to mixing will be shown later.

3.6. Resuspension

The advective transport from wind-induced wave action and slope processes is handled by several sub-models. The first sub-model (Fig. 4) concerns the calculation of the erosion and transport areas (ET-areas). To account for internal loading is a difficult matter, often considered an Achilles heel, in aquatic modelling. The following processes influencing internal loading are accounted for in this model (Håkanson and Jansson, 1983):

1. The sediment layer is divided into two parts: An upper biologically active layer and a 'geo-

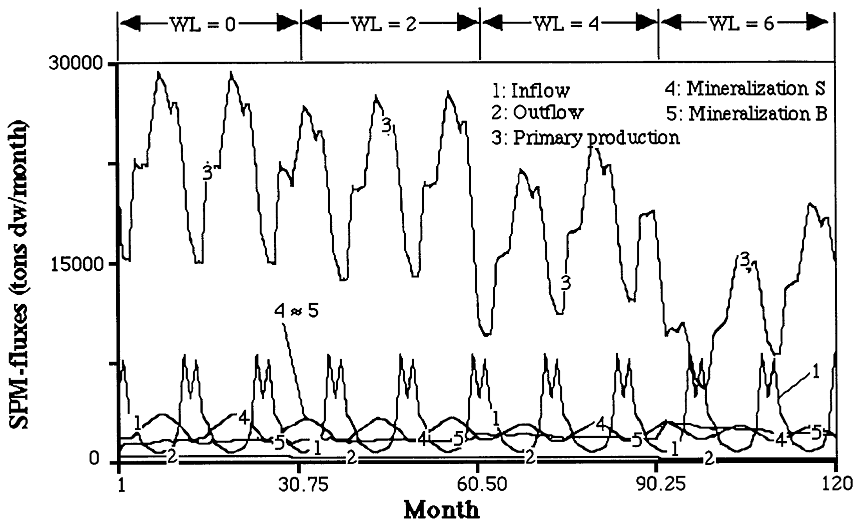

Fig. 3. Inflow, outflow, primary production, mineralization in surface water (S) and in bottom water (B) in Lake Kinneret, as predicted by the SPM-model for WL = 0, 2, 4, and 6 m.

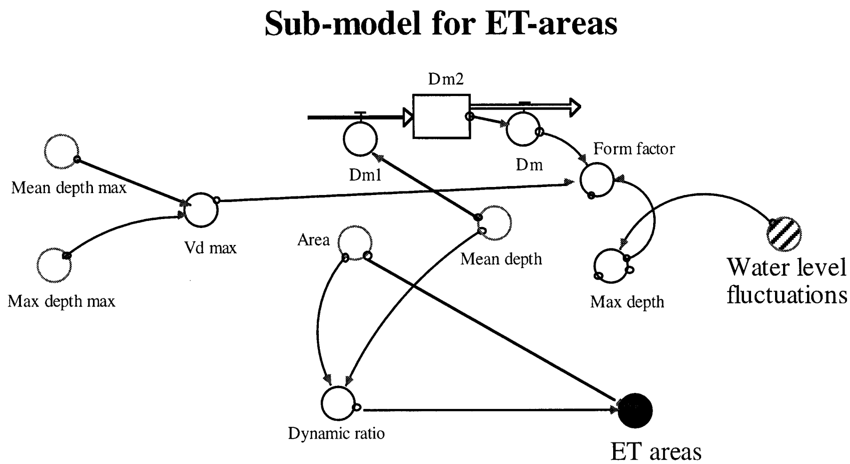

Fig. 4. An outline of the sub-model to determine ET-areas.

logical', biopassive layer. The thickness of the active layer is set to 5 cm (Håkanson, 1999).

2. Resuspension in lakes may be linked to:
   - an energy factor related to the effective fetch (here estimated as $\sqrt{\text{Area}}$; see Håkanson, 1999) and the water depth separating T- and A-areas ($D_{T/A}$, see later for definitions);
   - a form factor related to the percentage of the lake bed above $D_{T/A}$; and
   - a lake slope factor related to the fact that slope-induced transportation (turbidity currents) may appear on bottoms inclining more than 4–5%.

This information is used to estimate the bottom areas where processes of erosion (E), transport (T) and accumulation (A) prevail. E-bottoms are areas where the cohesive materials that follow Stokes's law are not deposited. Coarse deposits dominate such bottoms. T-bottoms are, by definition, bottom areas where the fine suspended materials are deposited discontinuously. In such areas, one generally finds mixed deposits. Soft A-bottoms appear beneath $D_{T/A}$ (often called the wave base), where the fine suspended materials may be continuously deposited. In lakes, ET-areas will generally cover at least 15% of the bottom (in the shore zone where wind/wave action dominates the bottom dynamic conditions; Håkanson and Jansson, 1983).

For lakes larger than 1 km^2, ET can be determined by the following formula (from Håkanson and Jansson, 1983), which is also used in this model:

$$ET = 0.25*DR*41^{(0.061/DR)} \tag{10}$$

where DR is the dynamic ratio (DR $= \sqrt{\text{Area}}/$Dm; Area = lake area in km^2; Dm = mean depth in m).

When there are changes in the water level (WL), there will also be changes in lake area, volume and mean depth. This is handled by another sub-model. First (Fig. 5), the changes in lake area are calculated from an algorithm given by Håkanson (1999), see Fig. 6. When there is a lowering of the water level (WL), or a connected change in the wave base (WB), the new lake area, and the new area beneath the wave base, are calculated from the equation given in Fig. 6. Area is here a function of the maximum area (Amax), the maximum depth (Dmax), the changes in WL or WB, and the form factor (= volume development, Vd = 3*Dm/Dmax; see Håkanson, 1981, for further information about lake morphomerical parameters). The equation for the wave base (WB), i.e. the water depth separating areas of transport from areas of accumulation, comes from Håkanson and Jansson (1983).

$$WB = 45.7*((Area*10^{-6})^{0.5})/((Area*10^{-6})^{0.5} + 21.4) \quad (11)$$

where Area is given in m^2.

The changes in lake volume associated with changes in water level (WL) have been calculated by a standard formula (Håkanson, 1981). Note that these calculations could also have been done using the hypsographic curve for Lake Kinneret. This calculation, is, however, more general and this choice is not essential for the principles and processes included in the model or for the general validity of the results of the following simulations.

$$\text{If} \quad WL = 0 \quad \text{then} \quad Vol = Dm_{max}*Area_{max}$$

$$\text{else}$$

$$Vol = (Vol_{max} - ((Area_{max} - Area)*WL/2) - (Area*WL)) \quad (12)$$

The mean depth (Dm in m) associated with such changes in WL is given by the ratio Vol/Area.

The sub-model for resuspension from ET-areas plus erosion related to a lowering of the wave base (WB) is illustrated in Fig. 7. This sub-model handles all fluxes to and from the sediments and calculates the resuspension relative to all other fluxes. It should be noted that resuspension occurs from ET-areas to surface water, from ET-areas to bottom water and from a lowering of the wave base both to the surface water and the bottom water. Two distribution coefficients are needed to handle these fluxes. The resuspension from ET-areas is distributed either to surface water or to bottom water by means of the form factor, Vd/3, which is used as a distribution coefficient; Vd/3 of the amount available for resuspension on the ET-areas goes to bottom water and (1 − Vd/3) goes to the surface water (see Fig. 6; when Dm ≈

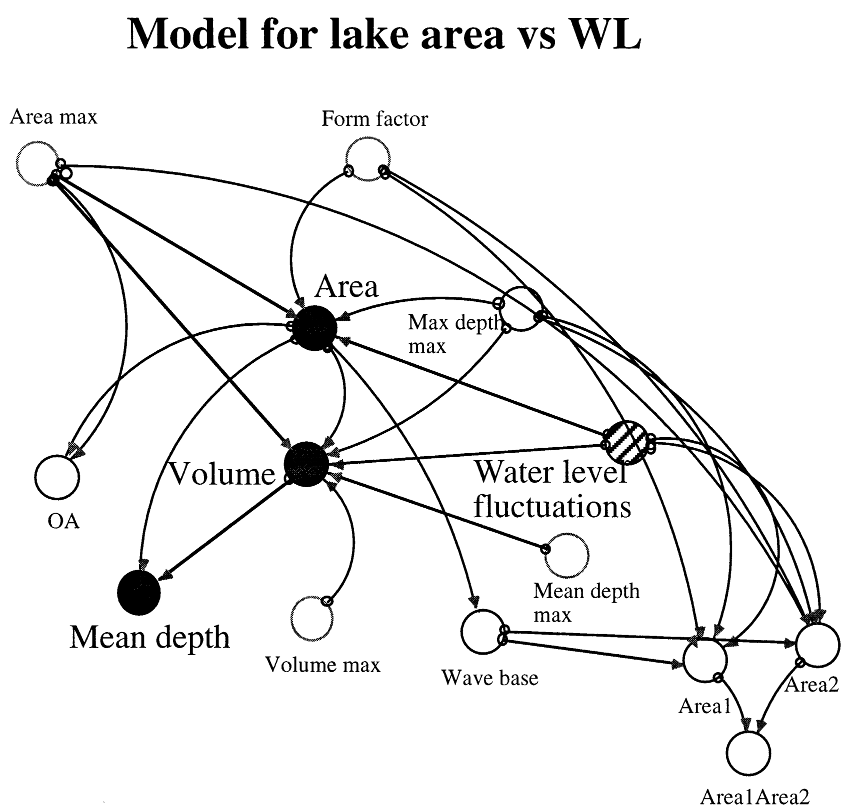

Fig. 5. An outline of the sub-model to calculate changes in lake area, volume and mean depth associated with water level fluctuations.

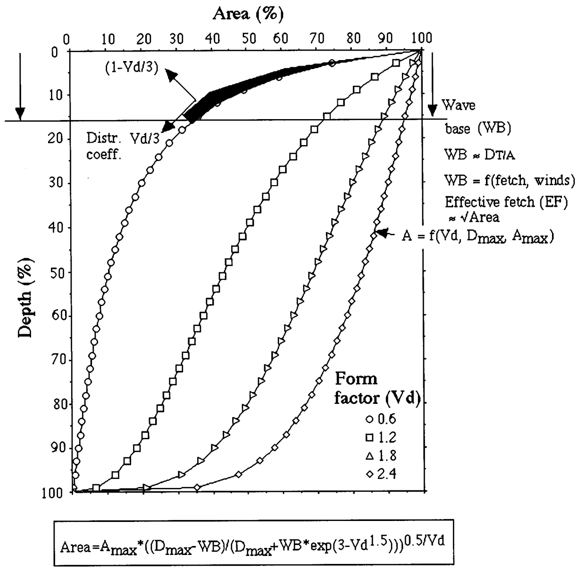

Fig. 6. Illustration of four relative hypsographic curves with different form factors (Vd). A lowering of the wave base, or a change in water level (WL), will influence the area above the wave base and the resuspension of matter on ET-areas. Vd/3 is used as a distribution coefficient to regulate the resuspended matter either to surface water (1 − Vd/3) or to the bottom water (Vd/3). The equation gives changes in lake area (Area) as a function of maximum area (Amax), maximum depth (Dmax), Vd and water level or wave base alterations (WL or WB).

Dmax, the lake is U-shaped and all resuspended matter from ET-areas should go to the bottom water; see Håkanson, 1999, for further information).

The distribution coefficient handling erosion related to a lowering of the wave based is set to 0.5, as a default assumption. This means that 50% is assumed to be transported to the surface water and 50% to the deep water of the matter available when the wave base is lowered. To quantify this amount is very problematic. The following approach has been used in this model. The area exposed to erosion is calculated as the difference between the areas above the wave base at WL = 0 (Area1 in Fig. 7) and above the wave base when the water level is lowered (Area2). The erosion depth is set to 5 cm as a default assumption. The larger the WL-value, the larger the areas exposed to resuspension and the larger the erosion depth. So, the erosion depth describes how sediments below the wave base will come above the wave base when the water level is lowered. These sediments may have been deposited a long time ago, and they are likely more compacted than recently deposited sediments. So, it is assumed that the lowering of the wave base may erode 5 cm of sediments, but this also depends on the change in the water level: a greater change in WL (related to WL = 0) means a greater erosion depth. This means that the erosion depth (ED in m) should be a function of the changes in water level. In this model, it is simply given by:

$$ED = 0.05 * WL \quad (13)$$

To calculate the amount of matter eroded, it is assumed that the water content of the sediments exposed in connection to a lowering of the wave base have a water content 10% lower than the default water content (= W = 80% wet weight (ww)) and a bulk density 10% higher than the default bulk density (= d = 1.1 g ww/cm^3). This means that erosion (EROS in tons dw/month) is calculated as:

$$EROS = 10^{-6} * (Area1 - Area2) * ED * (10^6) * d * 1.1 * (1 - (W - 10)/100) \quad (14)$$

The erosion related to a lowering of the wave base can only continue as long as WL > 0. The erosion rate (ER) is set to 1/24, as a default assumption. This means that all the material down to the erosion depth (ED) will be eroded and a new equilibrium established after 2 years. If, for example, the erosion depth is 2 dm (related to a water level of 4 m beneath the maximum value), then it would take 2 years to erode (by wind induced wave erosion) the material related to this lower wave base. If the water level is raised, then this type of erosion should stop. This is handled by the model (ERin, Fig. 7):

$$\text{If} \quad (WL - DELAY(WL,1)) > 0 \quad \text{then} \quad ERin = EROS \quad \text{else} \quad ERin = 0 \quad (15)$$

The difference (WL − DELAY(WL,1)) is simply the difference in water level between two calculations (dt).

3.7. Sedimentation

The last process discussed in this model presentation is sedimentation. All the previous parts of the model have been calibrated, but model-predicted values of sedimentation have been directly compared to empirical data (without any calibration). So, this is a critical model test, and it is important that the model yields realistic order of magnitude values for sedimentation. That would lend credibility to the following simulations.

There are four sedimentation fluxes:
1. SPM transport from surface water to bottom water;
2. SPM transport from surface water to ET-areas;
3. SPM transport from bottom water to A-areas; and
4. SPM transport from ET-areas to A-areas.

The same sedimentation rate is used to calculate sedimentation from surface water and bottom water. The calculation of ET-areas is based on

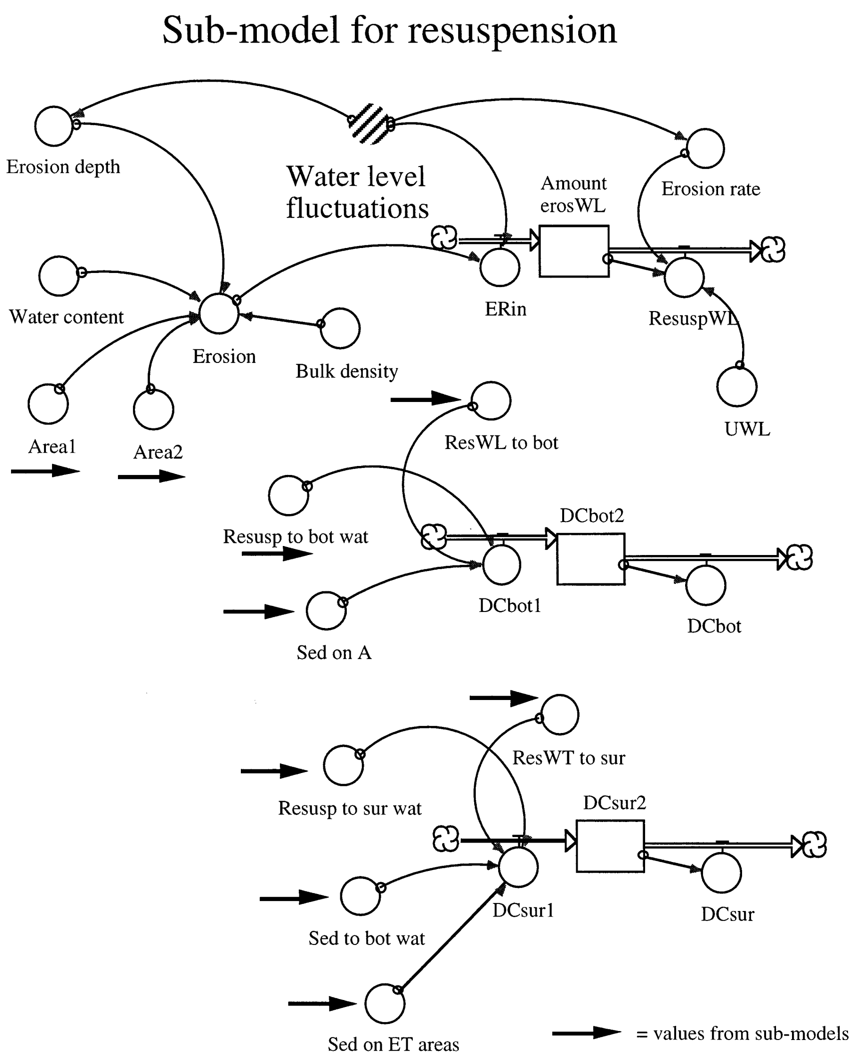

Fig. 7. An outline of the sub-model for resuspension and to calculate the distribution coefficient giving the fraction of resuspended matter relative to the total amount of suspended particulate matter in the water.

Håkanson and Peters (1995). ET is used as a distribution coefficient. The total sedimentation is distributed by this value on ET-areas and A-areas ($A = 1 - ET$), respectively.

Burban et al. (1990) have given data on the settling velocity of natural flocs tested in a flocculator. Typical values are then about 150–200 m/month. However, in natural waters the turbulence of the water influences the settling of the flocs and the movement of the water implies that the horizontal component working on the flocs would be at least ten times larger then the vertical (gravitational) component (Håkanson and Jansson, 1983). As such, the actual settling rate in natural waters could be at least ten times lower than the default value obtained in the experimental flocculator. Here, we will use a value of 500 m/year as a general default value for the settling velocity for SPM in lakes (from the LEEDS-models, see Håkanson, 1999). This means that the model is structured in such a manner that this value could be used as a general model constant and not as a lake-specific value. This value is divided by the mean depth (Dm in m) in the traditional way (Håkanson and Peters, 1995) to get a sedimentation rate (dimension 1/month). Burban et al. (1990) have demonstrated that also changes in the concentration of suspended matter influence the fall velocity for suspended matter. In this model, the calculated concentration of suspended matter will influence the settling velocity by means of a dimensionless moderator (see Håkanson and Peters, 1995, for further explanation). The amplitude value is calibrated in such a manner that a change in the concentration of suspended matter by a factor of 10, e.g. from 2 (which is a typical for oligotrophic lakes) to 20 mg/l (which is typical for eutrophic lakes), will cause a change in the settling velocity by a factor of 5. The normal value for the moderator is set to 2 mg/l and this means that the amplitude value is 0.45. This means that the sedimentation rate (KT) is given by:

$$KT = (500/12)*(1 + 0.45*(SPM/2 - 1))/Dm \quad (16)$$

However, this sedimentation rate is only used for the primary materials. Resuspended matter has a fall velocity which is set to be two times faster than the primary materials (Håkanson, 1999). Hence, the model uses a distribution coefficient (DC) to calculate the percentage of SPM that emanates from resuspension.

Table 8
Empirical data on sedimentation (dry weight/m^2 per day) in different months during 1994 from 15 and 35 m water depth using sediment traps and mean values (MV)

Month	Sed (15 m)	Sed (35 m)	MV
1	1.6	2.3	1.9
2	3.1	3.7	3.4
3	4.1	7.9	6.0
4	8.1	8.4	8.3
5	19.7	–	9.9
6	4.5	3.8	4.2
7	9.8	5.1	7.4
8	8.4	4.7	6.6
9	4.8	2.5	3.6
10	1.7	1.9	1.8
11	1.2	1.4	1.3
12	3.9	4.7	4.3

The available empirical data on sedimentation (Parparov, A., unpublished) in Lake Kinneret are given in Table 8. Because these data are from pelagic sites, they are only indicative of the mean monthly sedimentation in A-areas in the lake. There is a good correspondence in terms of order of magnitude between measured and modelled values for $WL = 0$ and $WL = 2$ (Fig. 8). However, if the WL is set to 4 or 6 m, there are major differences in SPM-sedimentation. Note that the given changes in WL will probably cause significant increases in sedimentation.

3.8. SPM predictions

The most critical model test is, evidently, for the target variable, SPM. Comparisons of empirical data of SPM from the lake during 1992 and 1996 (Table 6) with model predictions (Fig. 9) reveal that the model predicts SPM very well as long as $WL < 2$. A lowering of the water level to 6 m below the maximum level is predicted to drastically increase SPM in the lake. In this figure, there are also two levels for 'alarm' (related to

± 2*S.D.; 2*S.D. ≈ 95% confidence limits for SPM), which applies for a mean lake SPM of 3.4 mg/l. The S.D. values have been calculated from the available set of empirical monthly data given in Table 6 (S.D. = 1.13). Note that this standard deviation is based on the existing set of data. These values are 'not' valid for the entire lake volume but based on data from a few sampling sites. This means that the S.D. value is relatively high and the empirical 'alarm' limits relatively wide. It is probable that significant ecosystem changes would occur in Lake Kinneret if the mean monthly SPM values predicted by the model would appear outside these 'alarm' limits for a 'long' time. So, one must ask questions about the ecological relevance of the limits for 'alarm', the ecosystem consequences if SPM-values are maintained on the 'wrong' side of these limits of 'alarm' for a 'long' time, and how long is a 'long' time? Such questions cannot be addressed with this SPM-model but should be addressed when these results are discussed in wider contexts of lake management. This model can only provide data to make such discussions more relevant.

4. Uncertainty tests

All processes regulating SPM cannot be of equal importance. This means that one can accept greater uncertainties and larger simplifications for relatively unimportant processes than for more important processes. Generally, the key uncertainties are associated with the largest driving processes (inflow, outflow, production, sedimentation and resuspension; Håkanson and Peters, 1995), so such processes (Table 3) must be accounted for in the best possible manner.

The aim of this section is to give results from uncertainty analyses (using Monte Carlo simulations, according to procedures given in Håkanson, 1999) for Lake Kinneret to illustrate that there are crucial and less crucial uncertainties in this model (as in all models). Two main approaches to uncertainty analysis exist, analytical methods (Cox and Baybutt, 1981; Beck and Van Straten, 1983; Worley, 1987) and statistical methods, like Monte Carlo techniques (Tiwari and Hobbie, 1976; IAEA, 1988; Rose et al., 1989). In this section, we will only discuss Monte Carlo simulations.

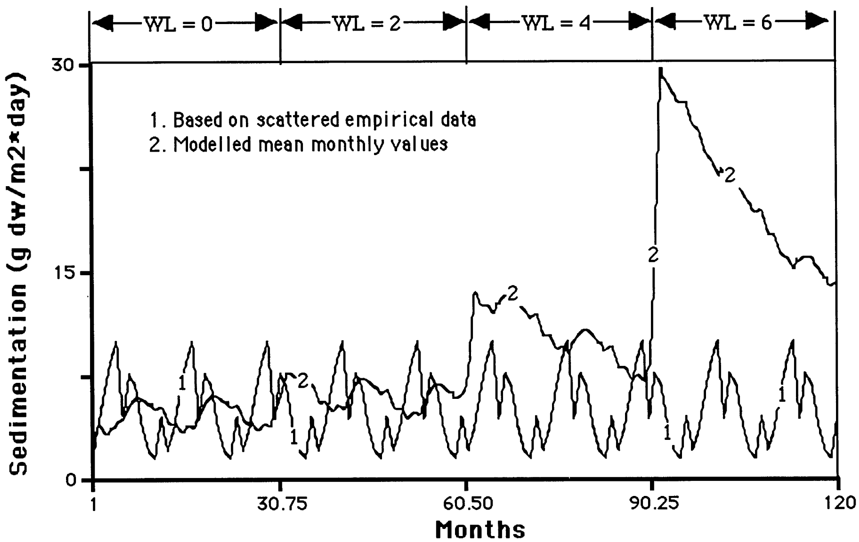

Fig. 8. A comparison between empirical data on sedimentation (Table 8) and model-predicted values for WL = 0, 2, 4 and 6 m. Note that the empirical data emanate from sediment traps sites for two water depths, and that the model predicts mean monthly values for A-areas.

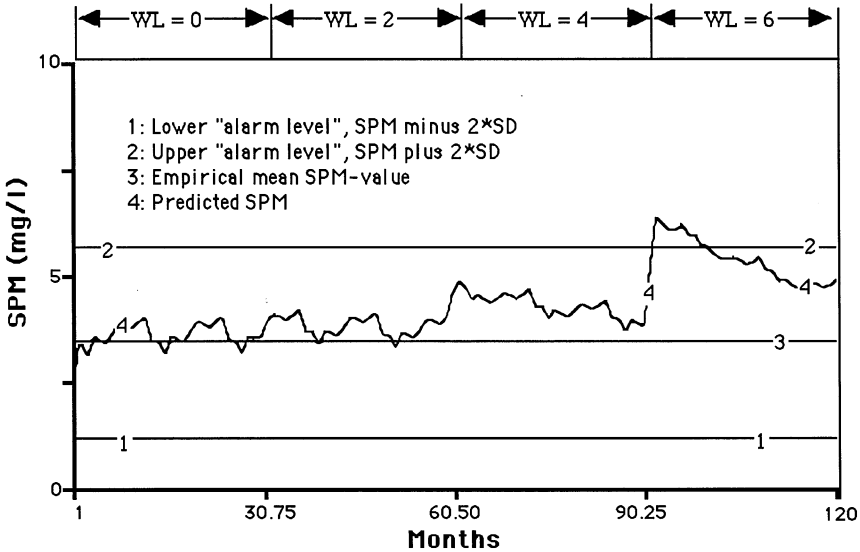

Fig. 9. A comparison between empirical data on SPM and model-predicted values for WL = 0, 2, 4 and 6 m. The lower and upper limits for 'alarm' are based on the mean empirical SPM-value (3.4 mg/l) ± 2 S.D. (S.D. = 1.13, corresponding to 95% confidence limits for individual values). Note that these are very wide limits when applied to the mean monthly SPM-values predicted by the model.

Uncertainty tests using Monte Carlo techniques may be done in several ways, using uniform coefficients of variation (CV = S.D./MV; mean value MV), or more realistically, using characteristic CV values (Håkanson, 1999). For predictive empirical or dynamical models based on several uncertain model variables (rates, etc.), the uncertainty in the prediction of the target variable (y) depends on such uncertainties. The cumulative uncertainty from many uncertain x-variables may be calculated by Monte Carlo simulations. So, Monte Carlo simulations is a technique to forecast the entire range of likely observations in a given situation; it can also give confidence limits to describe the likelihood of a given event. Uncertainty analysis (which is a term for this procedure) is the same as conducting sensitivity analysis for all given model variables at the same time. A typical uncertainty analysis is carried out in two steps. First, all the model variables are included with defined uncertainties and the resulting uncertainty for the target variable calculated. Then, the model variables are omitted from the analysis one at the time (see Fig. 10 for illustration).

The first step in the procedure is illustrated in Fig. 11, which gives a simulation where the PP value has been changed 100 times while all else in the model have been kept constant. In this case, it has been assumed that there exist a typical, characteristic mean value for PP, as calculated by the given equations, and a given uncertainty for this value given by the S.D., which has been set to 35% of the mean. That is, the CV value has been set to 0.35 for PP. From a normal frequency distribution (with a given mean value as predicted by the model and the given CV value) 100 data for PP have been selected at random (by the generator in the software 'I think') and used in the model to produce the 100 curves in Fig. 11 for the target effect variable, SPM. It is evident from Fig. 11 that the predictions of SPM are very sensitive to the value selected for PP. The following Monte Carlo simulations give results when all fluxes in the model have been varied.

Fig. 12 gives results from such uncertainty analyses for the dynamic SPM-model for Lake Kinneret, which is given here for demonstration (more realistic simulations follows). The water

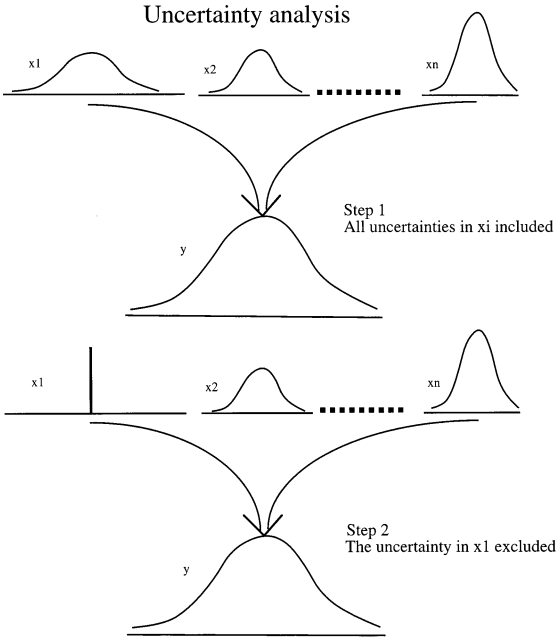

Fig. 10. Illustration of Monte Carlo simulations (= uncertainty analyses) as a two-step procedure (from Håkanson, 1999)

level was kept at WL = 0 for 12 months. Then (during month 13) WL was lowered to 4 m below the maximum value (Fig. 13) The corresponding changes in lake area and the target variable lake SPM (in mg/l) can be seen in curves 2 and 3, respectively in Fig. 13. The model predicts a marked increase in SPM associated with this hypothetical change in WL. Now, the question is: all fluxes in the model are more or less uncertain, and we have tested to see which uncertainties are most important. These would then be the parts of the model that would need further scrutiny and improvements. We have done 100 runs using Monte Carlo. Then we have taken out the data for months 10, 15 and 19, calculated SPM (mean values, standard deviations and coefficients of variation) when all uncertainties are accounted for (All) and when one at the time of the uncertainties associated with the given processes are omitted from the Monte Carlo simulations while all other uncertainties are accounted for. From Fig. 12A, one can note that for month 10 the uncertainties related to the sedimentation process are most important and the uncertainties for the primary production second most important. For month 15, i.e. after the hypothetical drastic change in WL (Fig. 12B), one can note that the values for SPM are much higher (about 6 mg/l as compared to about 3 mg/l) because erosion related to a lowering of the water level is now accounted for and that the peak values of SPM depend very

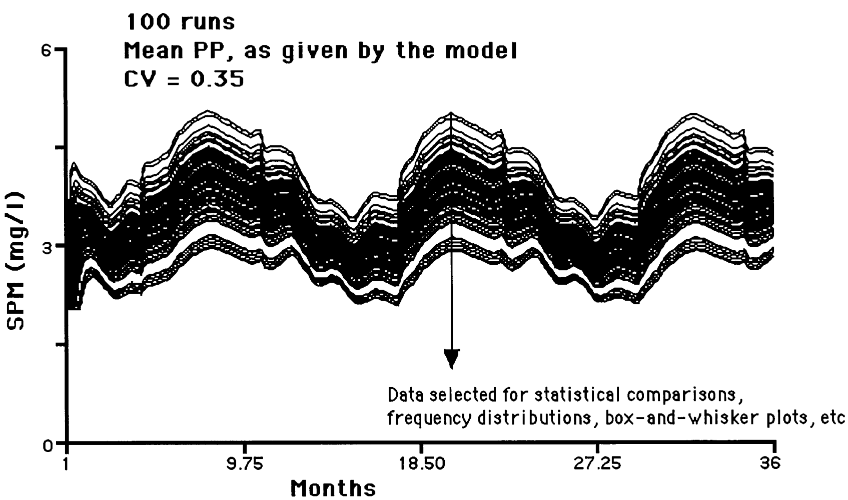

Fig. 11. Step one in the Monte Carlo simulations using the SPM-model (for WL = 0). The target effect variable is SPM and the primary production (PP) has been varied (CV = 0.35 and normal frequency distribution). One hundred runs. The figure also indicates that the following statistical analyses use data (MV, S.D. and CV = MV/S.D. for the month yielding highest SPM value).

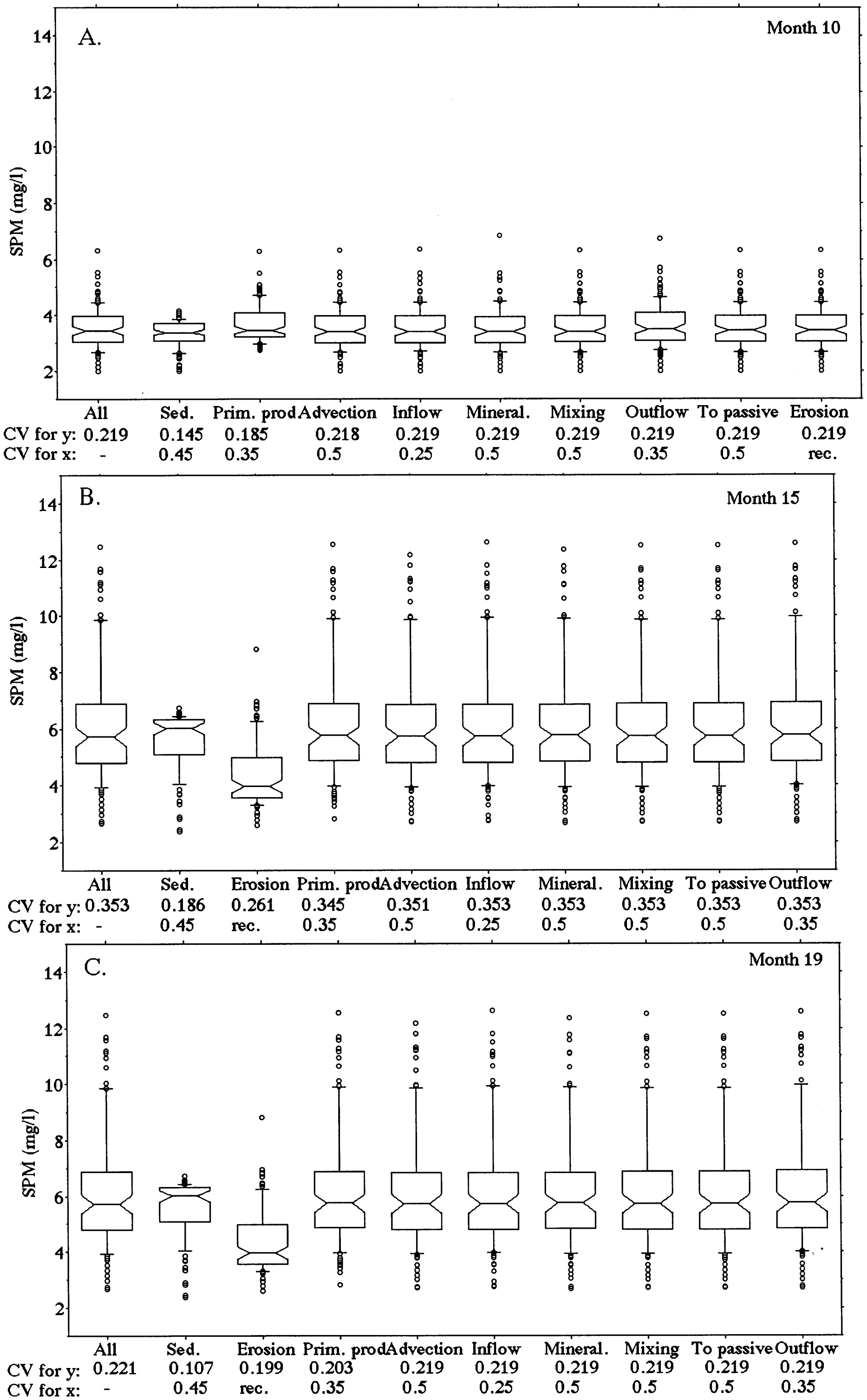

Fig. 12. Results of uncertainty analyses using the SPM-model for Lake Kinneret. All figures give calculated SPM-values on the y-axis, calculated CVs for the SPM-values as well as assumed CVs for the given processes. Upper: results for month 10, before changes in water level (the driving variable, see Fig. 13). Middle: results for month 15, 2 months after changes in water level (month 13). Lower: results for month 19.

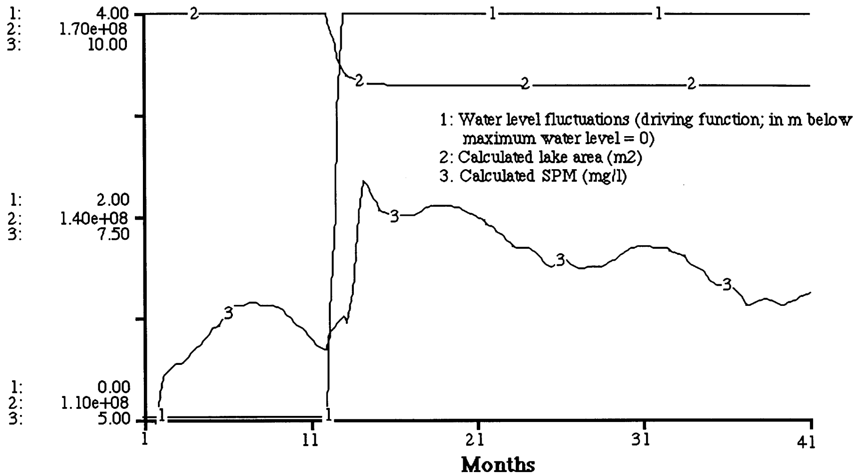

Fig. 13. Curve 1 gives the driving variable, water level fluctuations related to maximum area (WL = 0); curve 2 gives the calculated lake area related to the water level fluctuations; and curve 3 gives the target variable for these model calculations, the SPM-values.

much on the uncertainties related to erosion (i.e. a lowering of the wave base). Uncertainties for sedimentation are still most important but the uncertainties associated with the calculation of the erosion come next. The uncertainties for SPM month 19 (Fig. 12C) are also mostly related to uncertainties for the sedimentation rate and the erosion related to a lowering of the wave base.

We have used the following uncertainties for the fluxes (see also Fig. 12 and Håkanson, 1999):

Inflow: CV = 0.25; this uncertainty is relatively small since the values are derived from empirical data.

Outflow: CV = 0.35; this uncertainty is larger; it also includes evaporation from the lake surface, uncertain values for SPM in the outflowing water, etc. However, the outflow has been calculated in two ways (Table 7) and there is a good agreement between the two approaches, which motivates the CV-value of 0.35.

Primary production: CV = 0.35; the PP-fluxes are based on empirical data.

Sedimentation: CV = 0.45; these fluxes are also based on empirical data, but those data are relatively uncertain.

The CVs for all other processes have been set high, to 0.5. The uncertainties for erosion based on a lowering of the wave base are very difficult to assess. We have used values in steps (from 0.1 times the default value to ten times the default value for the erosion rate; called rectangular (rec), in Fig. 12) of the same probability.

These tests show that the crucial uncertainties concern:

- how to mathematically describe the sedimentation process and the uncertainty of the sedimentation process; and
- the resuspension (= erosion) related to a lowering of the wave base, and the uncertainty of this process.

All other processes, like inflow, outflow, mineralization, mixing, advection (= resuspension above the wave base), transport from active A-sediments to passive (= biopassive) A-sediments are generally of less importance for prediction mean monthly SPM in Lake Kinneret. For future work, we need to improve the sub-model for sedimentation and we need to have a much better grasp of the uncertainties associated with erosion related to a lowering of the wave base. This type of erosion may be studied by a tracer approach presented by Shteinman et al. (1997). It is evident that both erosion and sedimentation are very important and complex processes. This means that even very complicated models of SPM would be gross simplifications and hence uncertain. Those uncertainties need to be quantified and the only way to do that is by careful empirical studies.

To conclude: the processes of sedimentation and erosion related to a lowering of the wave base are of fundamental importance for SPM-predictions and it is important to try to minimise the uncertainties associated with these processes by further studies.

5. The worst case scenario and the question of 'critical' water level

The idea with this scenario is to illustrate the probable consequences of a more gradual, and more realistic sequence of water level fluctuations for the SPM-values in the lake, and also to try to identify the existence of any 'critical' threshold water level beyond which major changes in SPM-values are likely to appear. The following results suggest that a gradual decrease in water level by 6 m over 4 years seems to be a situation that would create very high fluxes of resuspended matter and large changes in SPM-values (Fig. 14). In this simulation, the water level changes are varied in a 'realistic' pattern. In other words, WL is lowered about 2.5 m each year with a recovery of 1 m each winter and the scenario corresponds to a 4-year drought.

The predicted SPM-values reaches the upper limit for 'alarm' in this scenario already in the end of the summer of the second year of drought (after month 48). Over the following 2 years of continuing drought, SPM increases far beyond the upper limit 'alarm' value, and even after 3 'rainy' years of increasing WL, SPM remains above this limit. The primary factor involved in the increases in SPM, as suggested by the uncertainty analyses and as shown in model predictions, is erosion related to a lowering of the wave base (Fig. 15). The erosion related to such a lowering of the wave base would increase the SPM-fluxes by a factor of 50–100, as compared to a situation with WL = 0.

6. Conclusions

The main conclusions from this work are:

1. A new model for SPM-fluxes applied to Lake Kinneret has been presented.
2. Uncertainty analyses (Monte Carlo simulations) have shown that the two most important model uncertainties concern sedimentation erosion related to and a lowering of the wave base. All other fluxes are of

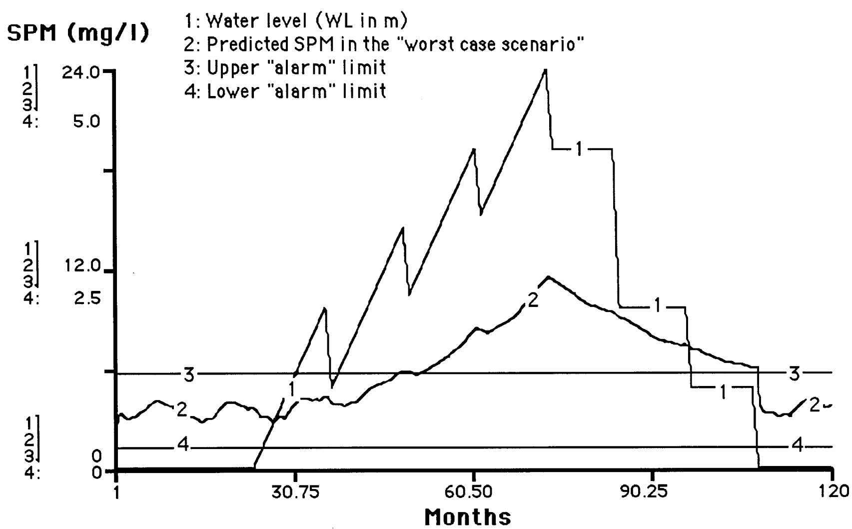

Fig. 14. Results for the scenario with a gradual lowering of the water level. The lower and upper limits for 'alarm' are based on the mean empirical SPM-value (3.4 mg/l) ± 2 S.D. (S.D. = 1.13, corresponding to 95% confidence limits for individual values). The driving function for these simulations is curve 1, the assumed changes in water level.

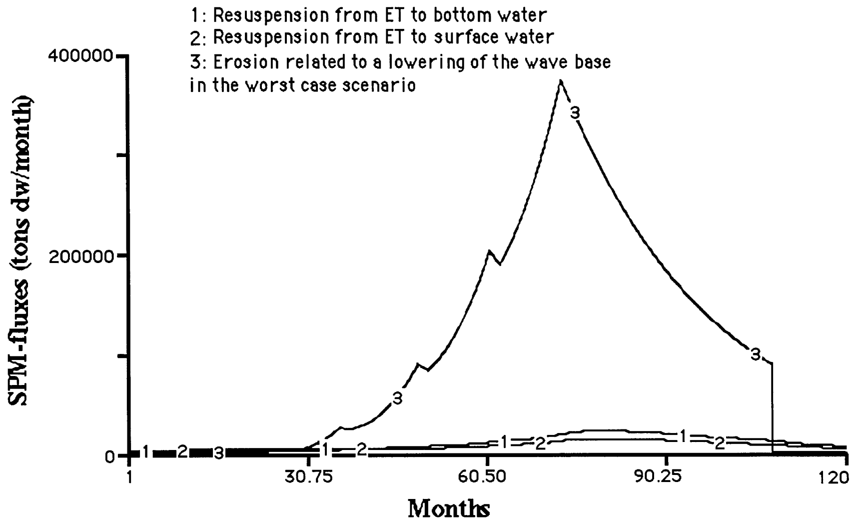

Fig. 15. Resuspension and erosion fluxes in the scenario with a gradual lowering of the water level.

less importance (e.g. inflow, outflow, primary production internal loading above the wave base, mineralization and mixing).

3. A successive, gradual lowering of the water level by 6 m over 4 years seems to correspond to the 'worst case' scenario likely to alter initial SPM-values the most.
4. In the 'worst case' scenario, very high levels of SPM are maintained for years following a return to high water levels.

There are many other possible consequences of a lowering of the water level in Lake Kinneret below the present minimum level. Such water level changes could, potentially, influence production/biomasses of key species of fish which need to access shoreline stones as spawning sites, or lake internal loading of nutrients, which influence primary and secondary production of important functional groups (like zooplankton and fish). It is evident that the use of water must be dimensioned to match the supply of water.

Nomenclature

CV	coefficient of variation (= S.D./MV, S.D. = standard deviation; MV = mean value
d	sediment bulk density (g ww/cm^3)
DR	dynamic ratio ($=\sqrt{\text{Area}}$/Dm; Area = lake in km^2; Dm = mean depth in m)
dw	Dry weight
EpiT	epilimnetic temperatures in °C
ET	erosion and transport areas (a distribution coefficient between 0 and 1; 1 means that areas of erosion and transport dominate 100% of the lake bottom)
HypoT	hypolimnetic temperatures in °C
KT	sedimentation rate (per month)
MinS	mineralization in surface water (*S*) (in g dw/month)
MixR	mixing rate (per month)
PP	primary production (generally in g dw/month)
PF	particulate fraction (dimensionless)
Q	water discharge (generally in m^3/month)

SPM	suspended particulate matter (mg/l)
Tw	theoretical lake water retention time (months)
Vd	volume development (= form factor; Vd = 3*Dm/Dmax; Vd/3 is used as a distribution coefficient for resuspension)
W	sediment water content (% ww)
WB	wave base (the water depth separating areas of transport and accumulation, $D_{T/A}$)
WL	water level (here related to max. water level in Lake Kinneret; WL = 2 m means that the water depth has been lowered 2 m relative to the max. water level)
WW	wet weight
Y_{Sec}	a dimensionless moderator (Y) for Secchi depth (Sec)

Acknowledgements

This work has been financially supported by the INTAS project 'Development of a system of water quality indices for lakes as a tool for management' and the National Swedish Research Council project 'Suspended matter in aquatic systems — methods, models and applications for lake, rivers and coastal areas'. We would like to express our thanks to Y. Geifman and the Mekorot Water Company–Kinneret Watershed Unit for data on Jordan River inflows and SPM concentrations and water outflows and Y. Yacobi for data on primary production. All other empirical data from Lake Kinneret used in model development are from the Lake Kinneret database and have been used with permission.

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