

Thesis Aquatic Ecology and Water Quality

Generic models for phosphorus retention in shallow lakes. A multi-lake study

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Abstract

To prevent lakes from eutrophication, criteria for in-lake total phosphorus concentrations are laid down in laws in several countries. A simple formula that establishes the relation between lake phosphorus loading and in-lake total phosphorus concentration can be used as a tool to calculate the specific loading that is needed to reach these concentrations. Literature gives simple relations based on hydraulic residence time. The shortcomings of these Simple Loading models (SL-model) are that they only fit for one lake or for more lakes with a certain range in lake properties. To find a model that is usable for lakes with a wider range in lake properties, we extended the simple models with explicit lake internal phosphorus fluxes and developed four new models by changing the internal loading description. In two Wind-induced Internal Loading models (WIL-models) the loading flux was related to wind-induced resuspension. For one of them (WIL_D-model) a detailed wind-induced resuspension theory was used which was been approached in the other model (WIL_S-model). Next, we developed two lake Shape related Internal Loading models (SIL-models) with internal loading related to lake area for the first (SIL_A-model) and to shoreline length for the second (SIL_M-model). Multiple regression has been used to estimate the calibration parameters in the models for the best coefficient of determination (r^2). This was done with varied data of twenty-two shallow lakes.

The SL-models gave low results ($r^2 \leq 0.27$) which corresponds with the hypothesis that models with only the hydraulic residence time as a predictor variable are unfit for multi-lake purposes. The results of the WIL-models were unsatisfactorily. The WIL_D-model gave a r^2 of -0.07. The WIL_S-model gave a high r^2 (0.8), but the calibration parameters were not in line with the approximated theory. It looks like that wind is not the most important predictor for internal phosphorus fluxes in our lakes. Internal loading related to shoreline length (SIL_M-model) gives the highest r^2 -value (0.82). The calibration parameters make the in-lake total phosphorus concentration decreasing with an increase of lake area or shoreline length. The most plausible hypotheses for this are that smaller lakes are more sensitive to phosphorus input from adjacent land than bigger lakes and that a longer shoreline length gives more changes for the origination of water purifying helophyte beds.

Keywords: phosphorus models, phosphorus retention, wind-induced resuspension, internal loading, sedimentation, shallow lakes, wind-wave theory, multi-lake study, shoreline length, lake shape, area, the Netherlands, Vollenweider.

Preface

I profess to be one of those who, by profiting, write, and by writing profit. (Augustine, Epist. 7)

Before you is the result of my thesis for the Wageningen University. The result of months work, reading, modeling, discussing, excel-ing, RSI-ing, writing and so on. I was supervised by Peter Schippers and Jeroen de Klein, researchers of the chair group Aquatic Ecology and Water Quality. In exceptional case, the report is not written in the format of the chair group, but written in that of a journal article of Ecological Modeling extended with a table of contents. The change is there that the article will be placed in this or changed form. It was educational to do it in this way.

My first thanks go to Peter for his close support. He gave me a glance in the life of a scientist. I saw the problems that can be met and learned how to deal with it. I saw and feel the pleasure of a sudden right insight in a problem. But above all, I learned that a scientist can be a normal, interesting person with his own ambitions, questions of life and death and domestic worries and happiness. So, it was not surprisingly that our talks frequently run out of time due to interesting conversations which had nothing to do with the thesis.

A second thanks to Jeroen de Klein, my second supervisor, for reading the report and giving constructive criticism. We did not meet many times, but the contacts were good. A special thanks to Mariek de Vries for her patience in helping me in regard to writing in understandable English. Without her advises, the legibility of the report would be less clear. Thanks to all other persons who were important for me the last time.

Last but not least, thanks to the Lord, Creator of this world. All my energy, wisdom and health have been a free gift from Him. May everything be in His honour.

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Contents

| | |
|---|-----------|
| 1. INTRODUCTION | 4 |
| 2. GENERAL APPROACH | 5 |
| 3. SIMPLE LOADING MODELS (SL-MODELS) | 7 |
| 4. INTERNAL LOADING MODELS (IL-MODELS) | 11 |
| 4.1. BASIS MODEL | 11 |
| 4.2. WIND-INDUCED INTERNAL LOADING MODELS (WIL-MODELS) | 12 |
| 4.3. SHAPE RELATED INTERNAL LOADING MODELS (SIL-MODELS) | 16 |
| 5. DISCUSSION AND CONCLUSION | 18 |
| 5.1. SIMPLE LOADING MODELS (SL-MODELS) | 18 |
| 5.2. WIND-INDUCED INTERNAL LOADING MODELS (WIL-MODELS) | 18 |
| 5.3. SHAPE RELATED INTERNAL LOADING MODELS (SIL-MODELS) | 18 |
| 5.4. MAIN CONCLUSIONS | 20 |
| REFERENCES | 21 |
| APPENDIX A - VARIABLES AND PARAMETERS | 24 |
| APPENDIX B - SEDIMENT RESUSPENSION MODELS | 25 |

1. Introduction

Eutrophication is a major problem for water management in the world. The enrichment of lakes by high nutrient loadings causes abundant algal growth, which in turn reduces the natural and economical values of lakes (Van der Molen, 1999; Scheffer, 1998; Søndergaard et al., 2001). Algal biomass may be limited by phosphorus, nitrogen, light or other factors. External phosphorus loading, however, is widely considered to be the most important controlling factor in lake restoration (Vollenweider and Dillon, 1976; Hosper, 1997; Søndergaard et al., 2001). In several countries criteria for phosphorus lake concentrations are laid down in laws. Therefore, a simple formula that establishes the relation between loading and lake phosphorus concentration can be used as a tool to calculate the specific loading that is needed to reach these concentrations.

Vollenweider (1974, 1976; OECD, 1982) was one of the first to investigate relationships between nutrient loading and the effect of this loading on lake nutrient concentrations taking into account some important lake characteristics. He developed a simple lake concentration-input model that is based on hydraulic residence time. It can be applied to deep lakes for which apply a net internal phosphorus loss due to sinking processes. This makes the total phosphorus lake concentration lower than the total phosphorus inflow concentration.

In response to Vollenweider's work eutrophication research has been carried out for shallow lakes. These lakes differ from Vollenweider's deep lakes in that not all lakes have a net internal loss. This is due to higher internal loading fluxes caused by, for example, wind induced resuspension, phosphorus release from sediment, fish activities, mineralization processes and the absence of lake stratification (Portielje and Van der Molen, 1998; Scheffer, 1998; Søndergaard et al., 1999). Portielje and Van der Molen (1998) use a model that is based on the same principle as the Vollenweider model but with a production or loss rate k . Because of this parameter k the model can be used for both lakes with net internal loss and loading. However, the disadvantage of this model is that it can not be applied on a group of lakes that have mutual different internal loss and loading. The model only works for one lake or more lakes with similar lake characteristics (Portielje and Van der Molen, 1998). Without this disadvantage the model should be applicable for multi-lake approaches with a wider range of lake-types.

Therefore we have tried to find another, simple model about phosphorus lake concentration and lake phosphorus loading by describing the internal phosphorus fluxes in different ways. The requirements for this model are that it has to handle different lakes together with differences in characteristics and net internal loading. Moreover, it has to be more accurate than the above models and be appropriate for shallow lakes. To reach this aim, we developed four models, calibrated them with data of twenty-two shallow lakes (depth < 6m) and compared them with the k -model and Vollenweider's model.

2. General approach

This multi-lake study starts with a description of the Vollenweider (V-models) and Lijklema and Portielje models (*k*-models), called the Simple Loading models (SL-models). Adjusting the underlying mass balance and adding internal loading and loss relations gives the basis equations for the Internal Loading models (IL-models). Four models were developed by changing the internal loading description: two Wind-Induced Internal Loading models (WIL-models) and two Shape related Internal Loading models (SIL-models). Figure 1 shows the different model types with their models.

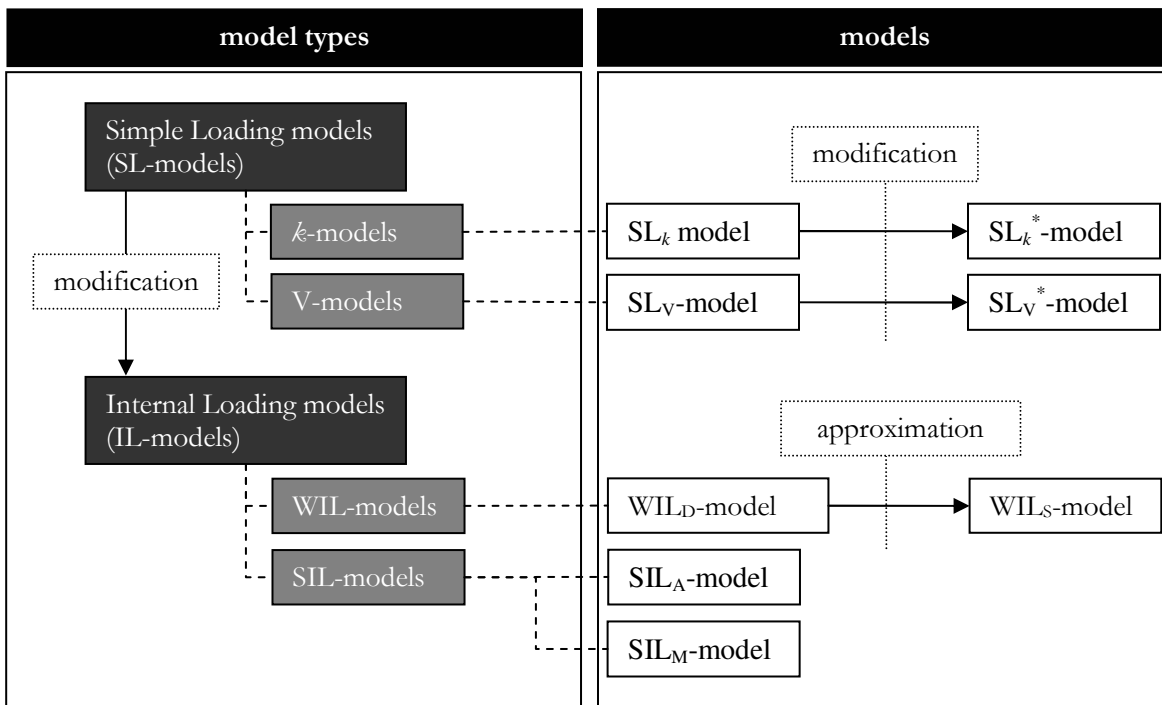


Fig. 1. Diagram with model types (left box) and models (right box) that have been described and developed. An arrow means that a model type or model is developed due to a modification or approximation of the former one. WIL means Wind-induced Internal Loading (D = Detailed, S = Simple) and SIL means Shape related Internal Loading (A = Area, M = shoreline length).

Multiple regression has been used to estimate the calibration parameters in the models for the best coefficient of determination (r^2). Also the adjusted coefficient of determination (r^2_{adj}) is calculated. Normally, r^2 improves with the used amount of predictor variables (P , P_{in} , etc.) in a model. r^2_{adj} Corrects r^2 for this effect which makes it possible to compare models with less or more predictor variables in a fair way (Devore and Peck, 1993). The results are given behind the description of each model. Varied data from twenty-two Dutch shallow lakes has been used (table 1). All used variable and parameter symbols with their meaning are collected in appendix A.

Tabel 1

The yearly mean values of different variables of 22 shallow lakes. The table shows maximum, minimum and mean values where D = depth, A = area, M = shoreline length, τ = hydraulic residence time, P = total phosphor concentration in lake water, P_{in} = total phosphor concentration in incoming water, W = wind speed. The years of observation are in brackets.

| Lake | $D^{1)}$ (m) | $A^{1)}$ (10^6 m ²) | $M^{3)}$ (m) | $\tau^{1)}$ (d) | $P^{1)}$ (g·m ⁻³) | $P_{in}^{1)}$ (g·m ⁻³) | $W^{2)}$ (m/s) |
|-----------------------------------|-----------------|---------------------------------------|-----------------|--------------------|----------------------------------|---------------------------------------|-------------------|
| Veluwemeer (1992) | 1.28 | 32.40 | 37033 | 44 | 0.093 | 0.141 | 5.0 |
| Wolderwijd (1992) | 1.50 | 18.00 | 17113 | 66 | 0.071 | 0.093 | 4.8 |
| Nuldernauw (1992) | 1.50 | 8.70 | 19267 | 26 | 0.110 | 0.223 | 4.6 |
| Drontermeer (1992) | 1.13 | 5.40 | 20438 | 11 | 0.157 | 0.179 | 5.0 |
| Braassemermeer (1980) | 3.90 | 4.52 | 8795 | 62 | 0.500 | 0.593 | 5.4 |
| Langeraars Plas Noordeinde (1980) | 1.90 | 0.75 | 3519 | 558 | 0.526 | 0.764 | 5.3 |
| Geerplas (1995) | 1.90 | 0.28 | 2192 | 431 | 0.436 | 0.317 | 5.3 |
| Nieuwkoopse Noord (1993) | 3.00 | 1.50 | 5589 | 475 | 0.064 | 0.130 | 4.6 |
| Nieuwkoopse Zuid (1993) | 3.00 | 1.00 | 4209 | 110 | 0.118 | 0.050 | 4.5 |
| Westeinderplassen (1980) | 2.80 | 8.52 | 14635 | 449 | 0.253 | 2.065 | 5.4 |
| Beulakerwijde (1983) | 1.50 | 13.00 | 15374 | 175 | 0.166 | 0.598 | 4.8 |
| Botshol Grote Wije (1995) | 1.40 | 1.00 | 4071 | 157 | 0.048 | 0.249 | 4.6 |
| Het Hol (1995) | 1.00 | 0.30 | 3313 | 157 | 0.062 | 0.172 | 4.2 |
| Loosdrecht (1991) | 1.80 | 9.79 | 13877 | 256 | 0.047 | 0.144 | 4.2 |
| Bergsche voorplas (89-90) | 2.00 | 0.60 | 3450 | 95 | 0.330 | 0.388 | 4.8 |
| Bergse achterplas (89-91) | 2.00 | 0.43 | 3176 | 105 | 0.420 | 0.424 | 4.8 |
| Waalboezem (1983) | 3.80 | 0.78 | 7352 | 190 | 0.210 | 0.562 | 4.6 |
| Binnenbedijkte Maas (1983) | 4.00 | 1.58 | 13592 | 273 | 0.210 | 0.374 | 4.9 |
| Brielsemeer (1983) | 5.50 | 4.91 | 17746 | 135 | 0.220 | 0.424 | 6.3 |
| Volkerak (1994) | 5.00 | 45.70 | 37499 | 95 | 0.140 | 0.281 | 5.3 |
| Zoommeer (1994) | 6.00 | 15.80 | 20376 | 55 | 0.180 | 0.133 | 5.3 |
| Nannewijd (1995) | 1.00 | 1.00 | 4800 | 157 | 0.161 | 0.142 | 4.6 |
| <i>Maximum</i> | 6.00 | 45.70 | 37499 | 558 | 0.526 | 2.065 | 6.3 |
| <i>Minimum</i> | 1.00 | 0.28 | 3176 | 11 | 0.048 | 0.050 | 4.2 |
| <i>Mean</i> | 2.60 | 8.00 | 12610 | 186 | 0.206 | 0.384 | 4.9 |

¹⁾ Portielje, 1998

²⁾ KNMI, 2002

³⁾ Have et al., 2003

3. Simple Loading Models (SL-models)

Phosphorus enters the lake in a particulate form or as dissolved phosphate. There is interaction between these two forms due to processes like adsorption and desorption by clay particles, uptake by algae and decay of organic matter. The particulate form is subject to sedimentation and resuspension processes. Resuspension increases the contact between particles containing phosphorus, and water. This may significantly affect the phosphorus release and internal phosphorus loading, while sedimentation causes a phosphorus loss (Hamilton and Mitchell, 1997; Søndergaard et al, 2001).

The change of the total phosphorus lake concentration can be given by a simple mass balance based on the external lake loading and the internal phosphorus loading or production. This mass balance with an equal in and outgoing discharge looks as follows:

$$\frac{dP}{dt} = (P_{in} - P) \frac{1}{\tau} - kP \quad (1)$$

where t is time (d), P is the total phosphorus concentration in lake water ($\text{g}\cdot\text{m}^{-3}$), P_{in} is the total phosphorus concentration in incoming water ($\text{g}\cdot\text{m}^{-3}$), τ is the hydraulic residence time (= volume/discharge, d) and k is a first order loss or production rate (d^{-1}) which is a result of all internal loading and loss processes together. For stationary condition ($dP/dt = 0$) the model is given by:

$$P = P_{in} \frac{1}{1 + k\tau} \quad (2)$$

which is used by Portielje and Van der Molen (1998). We have called this the SL_k -model. Fitting the SL_k -model on one specific lake can give high r^2 results. Portielje and Van der Molen (1998) give values in the range of 0.14 to 0.93. But the model is less accurate for multi-lake purposes when the denominator between the lakes much differs (Portielje and Van der Molen, 1998).

For $k = \sqrt{1/\tau}$ the Vollenweider formula is obtained (SL_v -model):

$$P = P_{in} \frac{1}{1 + \sqrt{\tau}} \quad (3)$$

where $\sqrt{\tau}$ has no theoretical background. It is a simplification of τ^x where x is a regression parameter with a value around 0.5 (Vollenweider, 1976). Due to this statistical nature the equation is dimensionally

incorrect. In both models τ is the key variable controlling the relationship between P and P_{in} . Note that the positive value of τ makes the fraction in the SL_V -model lower than 1. This means that in this model P is always lower than P_{in} and that the SL_V -model is unfit to describe lakes with net internal loading. This is in contrast to the SL_k -model (equation 2). There the parameter k can be both positive and negative which makes the fraction lower or higher than one.

OECD (1982) and Lijklema et al (1989) used a modified version of the Vollenweider model that is more suitable for Dutch shallow lakes (SL_V^* -model):

$$P = a \left(P_{in} \frac{1}{1 + \sqrt{\tau}} \right)^b \quad (4)$$

where a and b are fitting parameters with values of 1.02 and 0.88 in the case of OECD and 0.698 and 0.88 in the case of Lijklema. The SL_k -model (equation 2) can be modified in the same way as the SL_V^* -model, called the SL_k^* -model. The so obtained four models have been calibrated and the results are presented in table 2 and figure 2 and 3.

Table 2
Regression results for the Simple Loading Models (equation 2, 3 and 4), the three calibration constants and the two coefficients of determination.

| SL-model | a | b | k | r^2 | $r^2_{adj.}$ | P-value |
|----------|------|------|-------|-------|--------------|---------|
| V | - | - | - | -1.40 | -1.66 | 0.940 |
| V* | 1.13 | 0.46 | - | 0.26 | 0.18 | 0.022 |
| k | - | - | 0.007 | 0.06 | -0.04 | 0.012 |
| k^* | 0.54 | 0.55 | 0.005 | 0.27 | 0.19 | 0.012 |

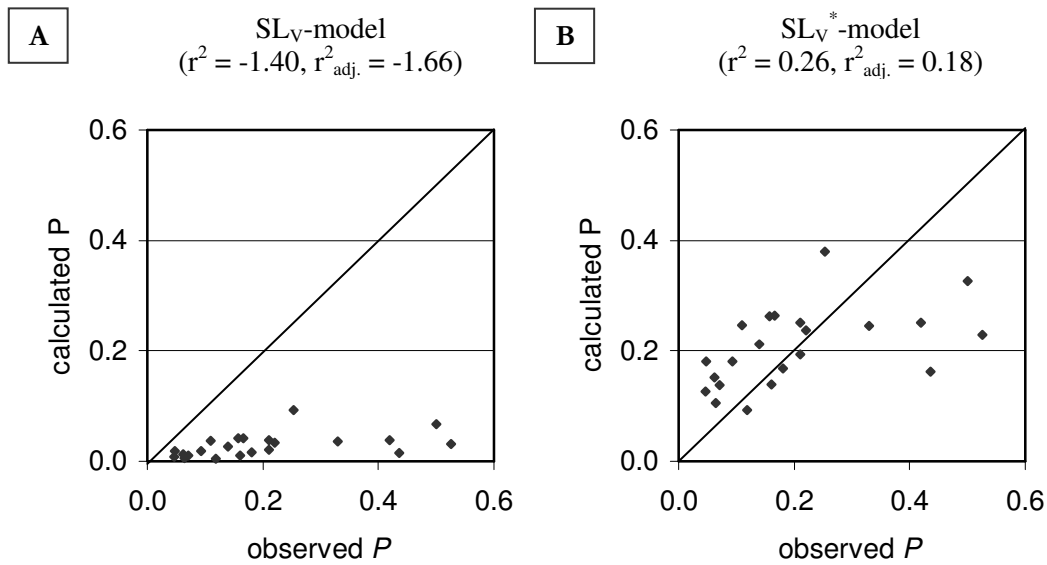


Fig. 2. P observed against P calculated ($\text{g}\cdot\text{m}^{-3}$) for A) the Vollenweider model (SL_V -model) and B) the modified Vollenweider model (SL_V^* -model). The lines are 1:1 lines.

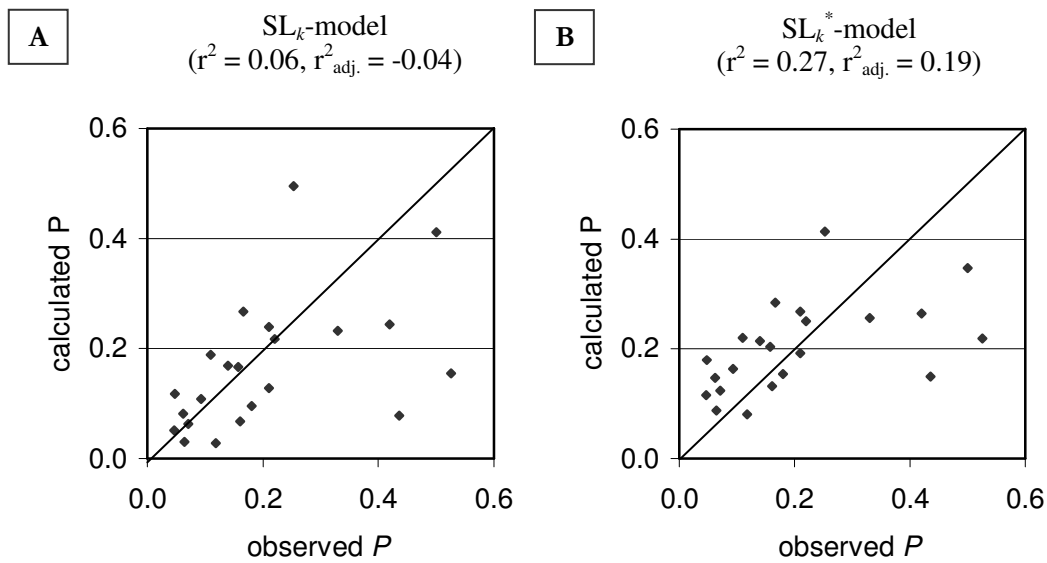


Fig. 3. P observed against P calculated ($\text{g}\cdot\text{m}^{-3}$) for A) the Lijklema and Portielje model (SL_k -model) and B) the adapted one (SL_k^* -model). The lines are 1:1 lines.

As might be expected, the SL_k and SL_V -models give low r -values for our multi-lake approach. Figure 2A shows clearly the underestimation of the SL_V -model for P . The other three figures show that most problems arise for the higher P -values. There the points are widely situated around the 1:1 lines. The addition of the fitting parameters a and b decreases the mutual differences in the r -values but does not result in much higher values. OECD and Lijklema give other values for a and b in the SL_V^* -model than we found (OECD: 1.02 and 0.88; Lijklema: 0.698 and 0.88). Especially b differs from the given values.

In spite of the modifications τ and $k\tau$ alone are unfit to control the relation between P and P_{in} . This could be expected regarding the correlation of τ with P and P/P_{in} in table 3. The τ - P correlation is just inversely proportional to the τ - P relations in the SL-models and the τ - P_{in} is very low.

Table 3

Correlations between the different lake variables and P/P_{in}

| | D | A | M | τ | P | P_{in} | W | P/P_{in} |
|------------|-------|-------|-------|--------|-------|----------|------|------------|
| D | 1.00 | 0.23 | 0.27 | -0.04 | 0.14 | 0.10 | 0.59 | 0.11 |
| A | 0.23 | 1.00 | 0.91 | -0.33 | -0.30 | -0.09 | 0.21 | -0.16 |
| M | 0.27 | 0.91 | 1.00 | -0.41 | -0.35 | -0.06 | 0.31 | -0.21 |
| τ | -0.04 | -0.33 | -0.41 | 1.00 | 0.31 | 0.47 | 0.09 | -0.19 |
| P | 0.14 | -0.30 | -0.35 | 0.31 | 1.00 | 0.40 | 0.49 | 0.20 |
| P_{in} | 0.10 | -0.09 | -0.06 | 0.47 | 0.40 | 1.00 | 0.37 | -0.37 |
| W | 0.59 | 0.21 | 0.31 | 0.09 | 0.49 | 0.37 | 1.00 | 0.01 |
| P/P_{in} | 0.11 | -0.16 | -0.21 | -0.19 | 0.20 | -0.37 | 0.01 | 1.00 |

4. Internal Loading Models (IL-models)

4.1. Basis model

The SL-models are black box models. They give no insight in the specific internal phosphorus loss or loading processes and in regarding the low results the models are too general. We want to get a more convenient P - P_{in} relation by replacing kP , the first order production or phosphorus loss, in the mass balance of the SL-models (equation 1) by the summation of in-lake phosphorus fluxes. Internal loading and loss fluxes are considered as simultaneous processes. This view is in accordance with the opinion of others (Teeter et al., 2001). The balance is:

$$\frac{dP}{dt} = (P_{in} - P)\frac{1}{\tau} + (I - O)\frac{1}{D} \quad (5)$$

where D is the mean lake depth (m), I is the internal loading flux of phosphorus ($\text{g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) and O the internal outgoing or loss flux ($\text{g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$). At equilibrium this yields:

$$P = P_{in} + (I - O)\frac{\tau}{D} \quad (6)$$

Processes like sedimentation of particles, algae, dead organic material and other phosphorus containing materials and phosphorus uptake by macrophytes cause internal phosphorus loss (Scheffer, 1998). The more the phosphorus containing sediment the higher the phosphorus loss and the more dissolved phosphorus the easier the phosphorus uptake by macrophytes. We supposed O to be proportional to P and substituted O by:

$$O = c_o P \quad (7)$$

This means that the fraction c_o ($\text{m}\cdot\text{d}^{-1}$) of P is considered as loss. Note that c_o has the same unit as sedimentation speed.

Combining O with equation 6 results in the basic IL-model:

$$P = \frac{P_{in} + I \frac{\tau}{D}}{1 + c_o \frac{\tau}{D}} \quad (8)$$

This basic equation has similarities with the SL-models (equation 2 and 3) for $I = 0$.

Also I can be substituted in different ways. So four new models have been obtained and calibrated in the next two paragraphs.

4.2. Wind-induced Internal Loading Models (WIL-models)

As said, resuspension of phosphorus containing particles causes internal loading. In shallow lakes resuspension of particles is induced predominantly by wind through wave action (Blom et al., 1994, Teeter et al., 2001). In this paragraph we will couple the internal phosphorus loading to wind-induced resuspension of phosphorus containing particles. It starts with a detailed theoretical model which is approximated by a simpler model later on.

Detailed Wind-induced Internal Loading Model (WIL_D-model)

Waves induce an orbital movement in water, leading to shear stress along the bottom. The shear stress is a function of wind speed, fetch (lake distance over which the wind blows) and water depth. Numerous relationships have been proposed, relating the resuspension flux either directly to the wind speed (Aalderink et al., 1985), wave height (Koncsos and Somlyódy, 1994), the maximum orbital bottom velocity (Blom et al., 1994), the squared maximum orbital bottom velocity (Van Duin, 1992) or to the bottom shear stress related to surface waves (Teeter et al., 2001). Based on several studies in shallow Dutch lakes (Van Duin, 1992) a relationship with orbital velocities is preferred above a description using bottom shear stress (Blom et al., 1994). The most simple in this genre is:

$$R = r(U_b - U_{b,cr}) \quad (9)$$

where R is the resuspension flux of particles ($\text{g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), r is the resuspension constant ($\text{g}\cdot\text{m}^{-3}$), U_b is the orbital velocity ($\text{m}\cdot\text{s}^{-1}$) and $U_{b,cr}$ is the critical orbital velocity ($\text{m}\cdot\text{s}^{-1}$), the minimal velocity needed for resuspension.

U_b is given by CERC (1984):

$$U_b = \frac{\pi H}{T \sinh(2\pi D/L)} \quad (10)$$

where H is the wave height (m), T is the wave period (s) and L is the wavelength (m). CERC (1984) gives more complex equations which are widely used to calculate H , T and L . They need D , fetch (F) and wind speed (W) as can be seen in appendix B. Because the wind directions and the accessory fetch values are unavailable in the dataset, F is approximated by $0.5 \cdot A^{0.5}$.

To know the phosphorus flux due to R the phosphorus mass fraction of the sediment is needed. We suppose that this fraction is formed in times of sedimentation and that the fraction does not change much while sediment is borrowed in the bottom of a lake. For sand or clay particles and algae is in force the higher the adsorptive or absorptive phosphorus concentration the higher the mass fractions of phosphorus until saturation is reached (Vollenweider, 1970; Wetzel, 1983). Just a fraction of P takes part in this process. As we want to calculate P , P_{in} is used as predictor for it. With this a Monod-type equation can be composed with some calibration constants which correct for the use of P_{in} instead of P :

$$f_p = c_f \frac{P_{in}}{c_h + P_{in}} \quad (11)$$

in which f_p is the mass fraction of phosphorus in resuspended particles (-) and c_f (-) and c_h ($\text{g} \cdot \text{m}^{-3}$) are calibration parameters. Note that c_h is a half saturation constant. For P_{in} is c_h the half of f_p is reached. Equation 9 and 11 together gives the internal loading flux:

$$I = c_l \frac{P_{in}}{c_h + P_{in}} (U_b - U_{b,cr}) \quad (12)$$

where $c_l = r \cdot c_f$ with a value > 0 . With equation 12, the basis equation 6 can be rewritten as:

$$P = \frac{P_{in} + \left(c_l \frac{P_{in}}{c_h + P_{in}} (U_b - U_{b,cr}) \right) \frac{\tau}{D}}{1 + c_o \frac{\tau}{D}} \quad (13)$$

This model has been calibrated. The results are presented in table 4 and figure 4A.

Approximation of the WIL_D-model (WIL_S-model)

The above resuspension theory is normally used in space or grid computer models with actual values of F , D and W instead of mean values (Teeter et al., 2001). The use of the rough data justifies an approximation of the CERC formula to get a model that can be used without the complex equations. The theoretical R out of equation 9 was approximated by a simple relation with some calibration parameters:

$$R \approx r(D^{c_D} F^{c_F} W^{c_W}) \quad (14)$$

where W is the wind speed ($\text{m}\cdot\text{s}^{-1}$), F is the fetch (m), c_D (value < 0), c_W (value > 0) and c_F (value > 0) are calibration parameters. r is again the resuspension constant. This together with the basic IL-model (equation 8) and equation 11 makes:

$$P = \frac{P_{in} + \left(c_I \frac{P_{in}}{c_h + P_{in}} (D^{c_D} F^{c_F} W^{c_W}) \right) \frac{\tau}{D}}{1 + c_O \frac{\tau}{D}} \quad (15)$$

We called this the WIL_S-model. F can be substituted by $0.5 \cdot A^{0.5}$ like in the WIL_D-model, but because of the calibration parameters we use simply A . The model has been calibrated and the results are presented in table 4 and figure 4B together with the results of the WIL_D-model.

Table 4

Regression results for the Detailed and the Simple Wind-induced Internal Loading Models, the calibration parameters and the two coefficients of determination.

| WIL-model | c_I | U_{bcR} | c_D | c_W | c_F | c_h | c_O | r^2 | $r_{adj.}^2$ | P-value |
|-----------|-------|-----------|--------|-------|--------|-------|-------|-------|--------------|----------|
| D | 0.041 | 0.0005 | - | - | - | 0.631 | 0.020 | -0.07 | -0.32 | 0.019 |
| S | 0.013 | - | -0.434 | 4.799 | -0.485 | 0.432 | 0.058 | 0.80 | 0.74 | < 0.01 |

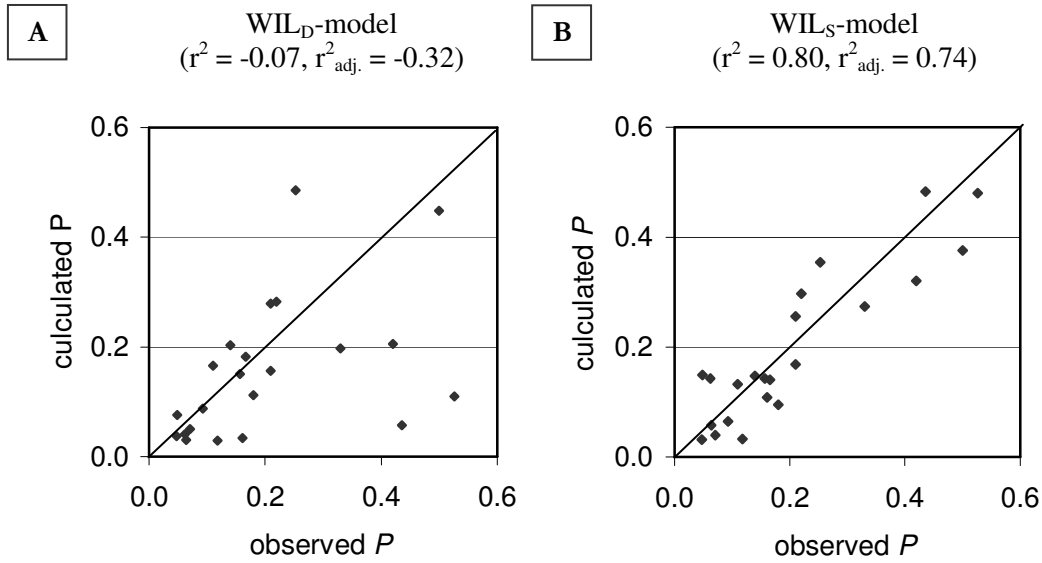


Fig. 4. P observed against P calculated ($g \cdot m^{-3}$) for the A) Detailed Wind-induced Internal Loading model (WIL_D -model) and the B) simple Wind-induced Internal Loading model (WIL_S -model). The lines are 1:1 lines.

It is clear that there is a great difference between the Detailed and the Simple WIL-model. The WIL_D -model gives no satisfactory result. Just as for the SL-models, figure 4A shows that the most problems arise for the higher P -values. The r -values of the WIL_S -model are high and also the graph (figure 4B) looks better. The cloud of points is well grouped around the 1:1 line. The calibration parameters for wind and depth are in accordance with the resuspension theory. However the negative value of c_F is against the theory that the bigger F , the more the internal loading. In this case the WIL_S -model is no approximation of the WIL_D -model. The F in the WIL_S -model is substituted by A and given the negative correlation between P and A in table 3, the c_F -value could be expected. These results suggest that wind-induced resuspension is not the most important predictor for internal loading in our shallow lakes.

4.3. Shape related Internal Loading Models (SIL-models)

The wide range in the data of area and shoreline length (table 1) gives thought that M and A could be important in predicting the in-lake total phosphorus concentration. Two calibrations have been done with the following internal loading formulas:

$$I = c_I P_{in}^{c_{P_{in}}} M^{c_M} \quad (16)$$

$$I = c_I P_{in}^{c_{P_{in}}} A^{c_A} \quad (17)$$

where $c_{P_{in}}$, c_M and c_A are calibration constants. These equations together with the basic IL-model (equation 8) give respectively the SIL_M-model and the SIL_A-model. M is the shoreline length (m) and c_A , c_M and $c_{P_{in}}$ are calibration parameters. Here P_{in} is not directly linked to sediment processes as done in equation 11, but is considered as historical loading. The higher this loading, the more the nowadays potential internal loading. In accordance to the equilibrium state of the model, the assumption is made that P_{in} does not differ much over the years and so the actual value is used. The models have been calibrated and the results are presented in table 5 and figure 5.

Table 5

Regression results for the Area and Shoreline length related Internal Loading models, the calibration parameters and the two coefficients of determination.

| SIL-model | c_I | c_A | c_M | $c_{P_{in}}$ | c_O | r^2 | $r_{adj.}^2$ | P-value |
|-----------|----------------------|--------|--------|--------------|-------|-------|--------------|---------|
| M | $1.12 \cdot 10^5$ | - | -1.875 | 1.006 | 0.040 | 0.82 | 0.77 | < 0.01 |
| A | $8.13 \cdot 10^{12}$ | -2.449 | - | 2.773 | 0.033 | 0.79 | 0.74 | < 0.01 |

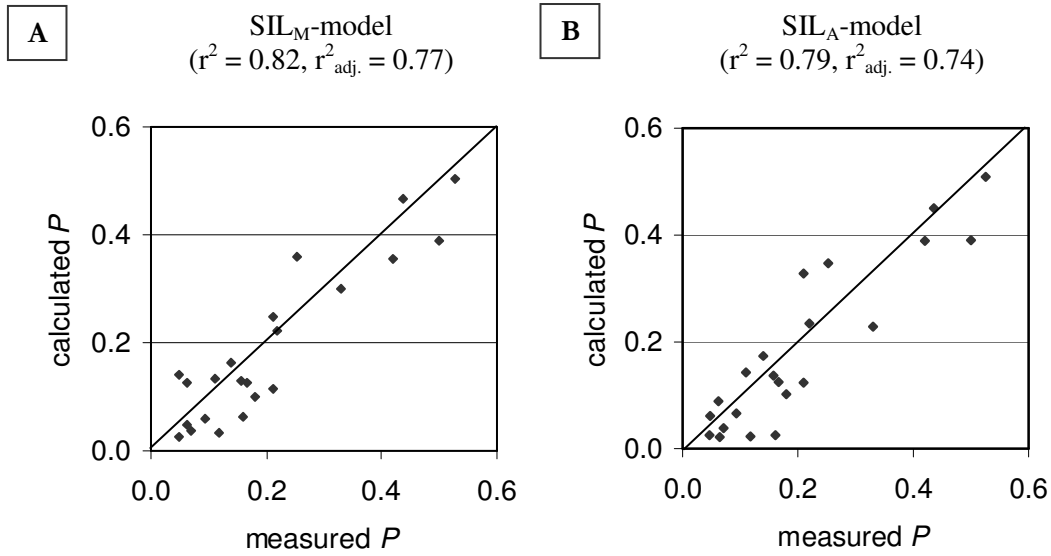


Fig.5. P observed against P calculated ($g \cdot m^{-3}$) for A) Shoreline length related Internal Loading model (SIL_M -model) and B) the Area related Internal Loading model (SIL_A -model). The lines are 1:1 lines.

The results are quite good. The r -values are high and the clouds of points well situated around the 1:1 lines. The SIL_M -model is the best of the two. The negative values of the calibration parameters c_A and c_M results in an decrease of P with an increase of M and A . Note that the length of the shoreline is closely related to area, see also the correlation in table 3, but not linear proportional to it. Two lakes with the same area can have different lengths of the shoreline due to difference in lake morphometry and so they can have different P -values.

5. Discussion and Conclusion

5.1. Simple Loading Models (SL-models)

The results of the SL-models are bad, especially the unmodified Vollenweider model (SL_V-model). For the other three models the most problems arise for higher P -values. This can be seen in figure 2B and 3. These results support the theory that the SL-models are not accurate for a multi-lake approach with mutual different denominator values. $k\tau$ Or τ alone are incapable for multi-lake purposes in predicting P (Portielje, 1998). This could be expected based on the correlation between P and τ in table 3 which is just inversely proportional to what might be expected based on the τ - P relations in SL-models.

5.2. Wind-induced Internal Loading Models (WIL-models)

Although the resuspension theory of CERC is a well predictor for sediment concentrations in lakes (Blom et al., 1998; Teeter et al., 2001), the Detailed WIL-model (WIL_D-model) gives very low r -values. In spite of the wide range in lake data and the used amount of predictors, the Simple WIL-model (WIL_S-model) gives quite good r^2 and $r^2_{adj.}$ -values. The values of the calibration parameters for wind and depth correspond to the resuspension theory. However, the negative value of the calibration parameter for the fetch (c_F) is in contrary to the theory that a higher F causes more resuspension and internal loading. In this case the WIL_S-model is no usable simplification of the WIL_D-model.

There are some possible reasons for these results. Usually, the CERC theory is used in a space or grid computer model with actual values for F , D and W instead of mean values (Teeter et al., 2001). The used lake-data might be too rough to get good internal loading values with the WIL_D-model. Moreover, the negative correlation of A with P (table 3) gives thought that wind-induced resuspension over one year is not the main reason of internal loading. The last reason can be that the differences in wind-data between the lakes are too small to explain the P differences.

5.3. Shape related Internal Loading Models (SIL-models)

The SIL-models are the best predictors of all calibrated models and easy to use due to less calibration parameters and predictor variables. The Shoreline length related SIL-model is the best of all.

Just as for the WIL_S-model, the Area related SIL-model (SIL_A-model) gives a negative value for the calibration parameter c_A . This negative value is the same for parameter c_M in the Shoreline length related SIL-model (SIL_M-model). It makes that there is a decrease of P from small lakes with a tight shoreline to greater lakes with a more twisting shoreline.

Several mechanisms can be hypothesized to explain the negative effect of lake area and shoreline length on the in-lake total phosphorus concentration. The first is that lake volume makes smaller lakes more

sensitive for phosphorus input from the adjacent land than bigger lakes. This can be demonstrated by a simple calculation. The input can consist of rain water, seepage, vegetable material, etc.

The second is about water plants. Helophyte beds of, for example, reed act as nutrient sink and reduce wind- and fish-induced resuspension of sediment (Headley et al., 2003, Gulati and Donk, 2002; Portielje and Rijdsdijk, 2003). Moreover, helophyte fields are refuges and forages fields for predator fishes that predate on benthivorous fishes (Scheffer, 1998). This predation reduces the fish-induced resuspension. Since helophytes occur in the area around the shoreline, it may be expected that the greater the shoreline length (M), the more the changes for helophyte fields to develop and the greater the above written effects. The last hypothesis is that greater lakes are deeper and therefore lesser sensitive to wind-induced resuspension.

Testing these hypotheses requires further research, but some indication can be derived from our data or from literature. It has often been shown that the abundance of submerged macrophytes decreases with water depth, largely because of light limitation (Van Geest et al., 2003). Although there is a positive correlation between area and depth in our data (table 3), the correlation is not high. So, this relation can be excluded. But, there is nearly no literature that gives a relation between abundance of macrophytes and lake area or shoreline length for our lake types. Van Geest et al. (2003) and Ogden (2000) analyzed vegetation structure of lakes in river floodplains. They found the opposite of our hypothesis for the area-macrophytes effect. However, Ogden did not separate the effects of water depth, which makes the exact reason unclear, and also Van Geest et al. is not able to give clear reasons for the found effect. For the effect of shoreline length on macrophyte abundance Van Geest et al. support our hypothesis. They found a positive effect of relative shoreline length (M/A) on macrophytes abundance. Note that the comparison between lakes in river floodplains and our lakes is not fair at all. Their lakes are frequently inundated which can cause other effect on macrophytes. Furthermore the lakes of Van Geest et al. are much smaller than our lakes (area between 0.0001 and $0.45 \times 10^6 \text{ m}^2$).

The last hypothesis about depth and sensitivity to wind-induced resuspension is improbable. As said, the correlation between area and depth is low (table 3) and the results of the WIL-models state that wind plays no important role in internal loading.

By the look of this, the first two hypotheses remain likely candidates for our lakes.

The SIL_M-model gets the final form by filling in the regression results and becomes:

$$P = \frac{P_{in} + 1.12 \cdot 10^5 P_{in}^{1.0} M^{-1.9} \frac{\tau}{D}}{1 + 0.04 \frac{\tau}{D}} \quad (18)$$

It will be interesting to get insight in the reliability of the model with other lakes and to know in which data ranges and states of equilibrium the model predicts well. The SIL-models can be used for evaluating the possible effects of changes in P_{in} and other variables. Note that all developed models assume the lakes to be in equilibrium ($dP/dt = 0$) and do not account for adaptation processes. Case studies in lake restoration showed a major resistance to recovery (Jeppesen et al., 1991; Van der Molen and Boers, 1994; Hosper, 1997) which may be explained by internal phosphorus loading from the sediments and homeostasis in the biotic community (Jeppesen et al. 1991). There are two equilibriums of importance: $dP/dt = 0$ and $df_p/dt = 0$. The first equilibrium is assumed in our models and will be established much sooner than the second equilibrium which can take years (Van der Molen et al., 1998). Therefore, in restoration purposes, it is recommended to use dynamic models to get insight in the precise lake development over time.

5.4. Main conclusions

The main conclusions are:

1. Predicting of total in-lake phosphorus concentration without explicit relations for internal phosphorus loading and loss does not work for multi-lake research with mutual differences in internal phosphorus loss and loading;
2. The wind-induced resuspension theory might be too precise to give good results with our mean values instead of actual values;
3. Due to the negative value of the calibration parameter for fetch (c_F), the Simple WIL-model (WIL_S-model) is no simplification of the Detailed WIL-model (WIL_D-model);
4. The results of the Wind-induced Internal loading models implies that wind-induced resuspension is not the main result for internal loading in our lakes;
5. Internal loading related shoreline length gives the best model (SIL-models) with a r^2 of 0.82;
6. The most important hypotheses for the SIL-models are that smaller lakes are more sensitive to phosphorus input from adjacent land than bigger lakes and that a longer shoreline length gives more changes for the origination of water purifying helophyte beds.

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Appendix A Variables and parameters

| Symbol | Description | first time used | Units |
|--------------|---|-----------------|--|
| A | lake area | eq. 15 | m^2 |
| a | fitting parameter for the modified SL-models | eq. 4 | |
| b | fitting parameter for the modified SL-models | eq. 4 | |
| c_A | calibration parameter for A | eq. 17 | |
| c_D | calibration parameter for D | eq. 14 | |
| c_F | calibration parameter for F | eq. 14 | |
| c_f | calibration parameter for f_p | eq. 11 | |
| c_h | calibration parameter as corrected half saturation constant | eq. 11 | $\text{g}\cdot\text{m}^{-3}$ |
| c_l | $= r \cdot c_f$ | eq. 12 | |
| c_M | calibration parameter for M | eq. 16 | |
| c_O | calibration parameter for O | eq. 7 | $\text{m}\cdot\text{d}^{-1}$ |
| $c_{P_{in}}$ | calibration parameter for P_{in} | eq. 16 | |
| c_W | calibration parameter for W | eq. 14 | |
| D | lake depth | eq. 5 | m |
| F | fetch | eq. 14 | m |
| f_p | phosphorus fraction in sediment | eq. 11 | - |
| H | wave height | eq. 10 | m |
| I | internal loading flux of phosphorus | eq. 5 | $\text{g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ |
| k | first order loss or production rate | eq. 1 | d^{-1} |
| L | wave length | eq. 10 | m |
| M | shoreline length | eq. 17 | m |
| O | internal loss flux of phosphorus | eq. 5 | $\text{g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ |
| P | total phosphor concentration in lake water | eq. 1 | $\text{g}\cdot\text{m}^{-3}$ |
| P_{in} | total phosphor concentration in incoming discharge | eq. 1 | $\text{g}\cdot\text{m}^{-3}$ |
| R | resuspension flux of particles | eq. 9 | $\text{g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ |
| r | resuspension constant for R | eq. 9 | $\text{g}\cdot\text{m}^{-3}$ |
| T | wave period | eq. 10 | s |
| t | time | eq. 1 | d |
| U_b | orbital velocity | eq. 9 | $\text{m}\cdot\text{s}^{-1}$ |
| $U_{b,cr}$ | critical orbital velocity | eq. 9 | $\text{m}\cdot\text{s}^{-1}$ |
| W | mean wind speed at 10m height | eq. 14 | $\text{m}\cdot\text{s}^{-1}$ |
| τ | hydraulic residence time (=volume/discharge) | eq. 1 | d |

Appendix B Sediment resuspension models

The next equations (CERC, 1984) are widely used to get H , L and T :

$$H = 0.283 \left(\frac{U_A^2}{g} \right) \tanh \left[0.530 \left(\frac{gD}{U_A^2} \right)^{3/4} \right] \tanh \left\{ \frac{0.00565 \left(\frac{gF}{U_A^2} \right)^{1/2}}{\tanh \left[0.530 \left(\frac{gD}{U_A^2} \right)^{3/4} \right]} \right\} \quad (1)$$

$$T = 7.54 \left(\frac{U_A}{g} \right) \tanh \left[0.833 \left(\frac{gD}{U_A^2} \right)^{3/8} \right] \tanh \left\{ \frac{0.0379 \left(\frac{gF}{U_A^2} \right)^{1/3}}{\tanh \left[0.833 \left(\frac{gD}{U_A^2} \right)^{3/8} \right]} \right\} \quad (2)$$

$$L = \frac{gT^2}{2\pi} \tanh \left(\frac{2\pi D}{L} \right) \quad (3)$$

where U_a is the wind-stress factor ($\text{m}\cdot\text{s}^{-1}$) ($= 0.71W^{1.23}$) used because of the non-linear relationship between wind stress and wind speed, F is the fetch (m), H is the wave height (m), T is the wave period (s), L is the wavelength (m), g is the gravity constant ($9.81 \text{ m}\cdot\text{s}^{-2}$) and D is the water depth (m).