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PHOSPHORUS LOADING ESTIMATION USING A FUZZY VOLLENWEIDER-IHACRES MODEL, MALAYSIA

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Eutrophication processes degrade lake or reservoir systems if not monitored and managed properly. This study estimates the phosphorus loadings for the Layang reservoir using the Vollenweider-IHACRES model. The IHACRES model was used to predict streamflow to the reservoir for the Vollenweider model. A fuzzy membership function was then used to describe phosphorus content, hydraulic loadings, and the phosphorus loadings representing the current conditions of the reservoir. The most likely range of phosphorus content was 0.1 to 0.3 mg/l and hydraulic loading was 1350 to 1400 m/yr. The average phosphorus content was 0.214 mg/l and average hydraulic loading was 1452 m/yr. The average calculated phosphorus loading was 0.6 g/m^2/yr (18.02 tons/year), within the estimated range of 0.26 to 0.81 g/m^2/yr (7.81 ton/yr to 24.28 ton/yr). The average daily inflow from the IHACRES model ranged from 4.95 to 2.99 m^3/s. The bias from the IHACRES model ranged from -0.5546 to -0.0076 mm/day. The R^2 values ranged from 0.9925 to 0.9208. Both statistics, in terms of bias and R^2 value, show that the model is able to perform well.

INTRODUCTION

Phosphorus, nitrates and sediment inflows into lakes and reservoirs will accelerate the process of eutrophication or lake aging. Reservoirs lose aesthetic values, the dissolved oxygen is depleted and fishes are killed. Reservoir eutrophication incurs economic losses in the forms of high raw water treatment costs, illness, depressed recreation industries, and management and restoration costs. Eutrophication processes tend to accelerate due to watershed disturbance by humans and this man-made acceleration is causing concern throughout the world.

Phosphorus (P) and nitrates (NO_3) are two important nutrients associated with eutrophication, but attempts to stop and reverse man-made eutrophication are focused on phosphorus. This is due to the difficulty in controlling the exchange of N between the atmosphere and water and the fixation of atmospheric N by some blue-green algae. Nitrogen can only be used for growth of organisms after being "fixed" (combined) into the form of ammonium (NH_4) or nitrate (NO_3) ions. Therefore, P is often the limiting element, and its control is of prime importance in reducing the accelerated eutrophication of fresh waters.

Phosphorus should be controlled at the source, either point sources or non-point sources. Focus on phosphorus loadings from non-point sources should be given attention because it has a significant influence over the water quality as much as from point sources. The accurate estimate of phosphorus loadings is needed in order to forecast and control the state of eutrophication of lakes and reservoirs (Shamsudin and Baharim, 2006; Heathwaite and Sharpley, 1999; Behrendt, 1999).

The phosphorus inflows into the Layang reservoir (Figure 1) were suspected to originate from agricultural activities within the Layang watershed (Supiah, 1997). The fertilizer from the agricultural activities causes an increase of eutrophication rate at the reservoir. This phenomenon must be investigated to develop a strategic plan to protect the overall reservoir water quality. The uncertainty or fuzziness of loadings estimation needs to be studied for the purpose of reservoir management and control measures.

The objectives of this study are as follows:

i) To estimate the phosphorus loadings in the Layang reservoir using the Vollenweider model.

ii) To predict the Layang river inflows into the reservoir using the IHACRES model.

iii) To incorporate a fuzzy membership function into the estimation of phosphorus loadings.

METHODOLOGY

Site description

The Layang reservoir in the Layang catchment area can be divided into two sections, the Hulu Layang reservoir and Hilir Layang reservoir (Figure 1). The reservoir is located in Masai, around 40 km travel distance from Johor Bahru city. The maximum altitude is 160 m while the minimum altitude is 30 m above the mean sea level. The area of the catchment lies approximately within coordinates of latitudes 1^o 30' to 1^o 36' N and longitudes 103^o 50' to 104^o 00' E.

The activities in the Layang river watershed are mostly villages, plantations and agricultural estates. These areas are the sources of potential pollution of the Layang river watershed when large amounts of fertilizers and pesticides are used.

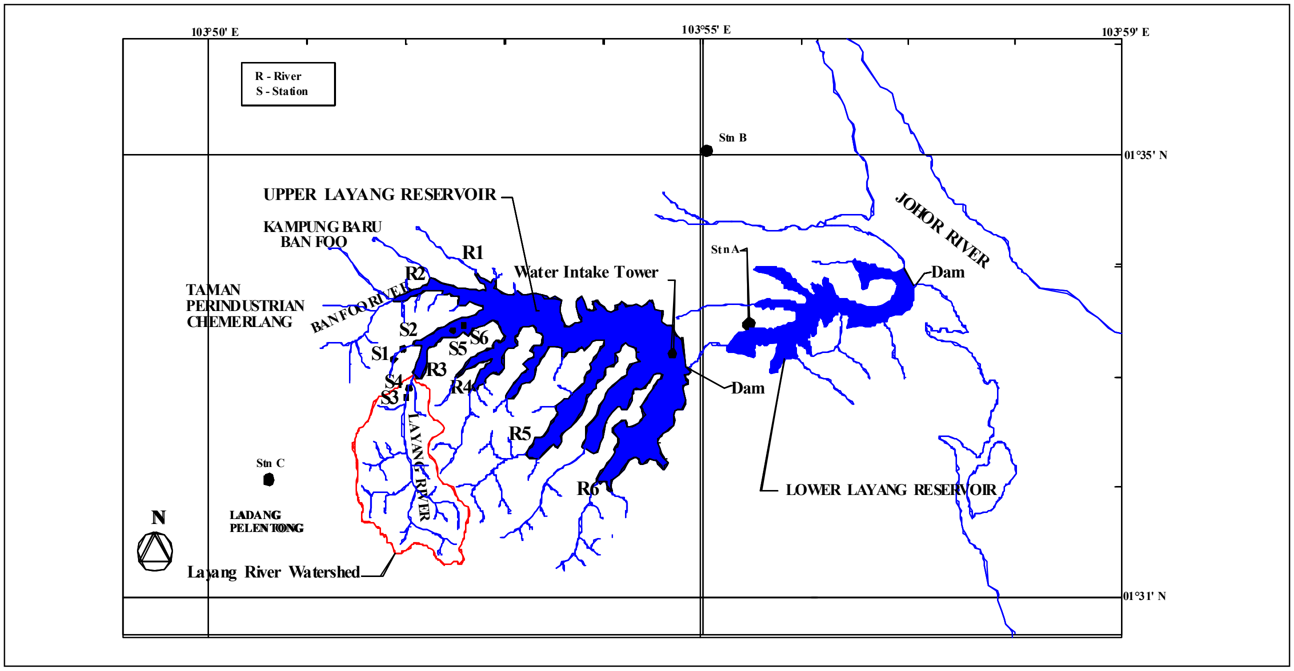

Figure 1. Location of Layang Reservoir.

Data collection

Three visits to the site were conducted on 21/12/2006, 10/01/2007 and 21/02/2007. The purpose of the visits was to take flow measurements and to obtain the water samples for analysis. The water samples were analyzed in the laboratory for phosphorus concentration using reagent phosVer 3 phosphates and a DR4000 spectrophotometer. The observed daily streamflow data (1997-2006) was also obtained from Strategy Tegas Sdn. Bhd (2006) and Universiti Teknologi Malaysia.

A current meter was used to measure the velocity of the main rivers that flow in the catchment area. The flow rates of the rivers were determined using the mid section method of the velocity-area method. The calculated flow rates are used to determine the baseflow used in the IHACRES model during periods of no rainfall.

Vollenweider model

Vollenweider model is one of the most practical models to estimate phosphorus loadings in lakes. Vollenweider developed a statistical relationship between phosphorus concentration and hydraulic residence time to predict lake area annual phosphorus loadings (Olem and Flock, 1990).

The equation for Vollenweider model is as follows:

$$Lp = P \,.\, q_s \,.\, (1 + \text{Ö}\, T_w) \qquad (1)$$

where

Lp is the annual areal P loadings (mg/m^2/yr)

P is the phosphorus concentration in water (mg/l)

q_s is the annual hydraulic loadings (m/yr)

T_w is the mean residence time of water in lake (yr)

IHACRES model

The IHACRES model was developed by the Institute of Hydrology in the United Kingdom and the Centre for Resource and Environmental Studies of Australian National University in Canberra. IHACRES stands for Identification of unit Hydrographs and Component flows from Rainfalls, Evaporation and Streamflow data. The IHACRES model software can be downloaded at www.toolkit.net.au/ihacres. The program operates on a Java platform and therefore must have the Java Runtime Environment installed before use.

The inputs of the model are a time series of rainfall, either temperature or potential evapotranspiration and observed streamflow. The output of the model is a time series of modelled streamflow.

The calibration function of the model has two modules in series, which are a nonlinear loss module and a linear unit hydrograph module as shown in Figure 2. The linear relationship between effective rainfall and streamflow enables the unit hydrograph theory to be applied. All of the non-linearity which is normally observed between rainfall and streamflow is accommodated in the nonlinear loss module that converts rainfall to effective rainfall.

The non linear loss module represents the transformation of rainfall to effective rainfall. Effective rainfall is the part of rainfall that leaves the catchment area as streamflow. A catchment that contains more moisture will generate more streamflow from a rainfall event compared to when the catchment is dry. This observation in employed in the form of a catchment wetness index, s_k and effective rainfall, u_k. The effective rainfall is a product of rainfall, r_k and the catchment wetness index, s_k (Jakeman and Hornberger, 1993).

$$u_k = r_k s_k \tag{2}$$

$$s_k = Cr_k + \left(1 - \frac{1}{\tau_w(t_k)}\right) s_{k-1} \quad s_0 = 0 \tag{3}$$

$$t_w(t_k) = t_w e^{0.062f(R-tk)}, \quad t_w(t_k) > 1 \tag{4}$$

where

u_k is the effective rainfall

r_k is the rainfall

s_k is the catchment wetness index

C is the mass balance term

t_w is the catchment drying rate at reference temperature

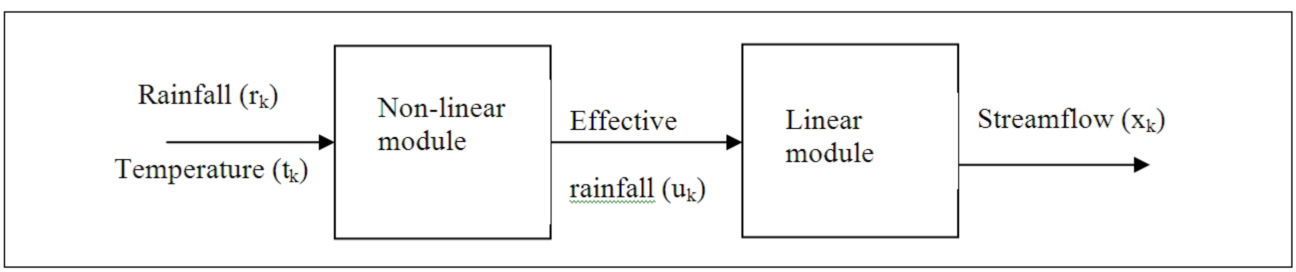

Figure 2. The system diagram of the rainfall - runoff model.

t_k is the temperature

R is the reference temperature

f is the temperature dependence of drying rate

Parameter t_w is the value of $t_w(t_k)$ at a reference temperature chosen by the user. In Equation 3, $t_w(t_k)$ controls the rate at which the catchment wetness index decays when there are no rainfall events. Parameter f controls the sensitivity of $t_w(t_k)$ to changes in temperature. For time intervals with rain, decay of catchment wetness index still occurs but it is also incremented by a proportional mass balance term of rainfall. A value for parameter C is selected so that the volumes of effective rainfall and observed streamflow over the model calibration period are equal. This value is calculated automatically during the model calibration.

The linear module of the model converts effective rainfall excess, u_k at time step k to streamflow, x_k. It can be executed by recursive application of Equation 5.

$$x_k = ax_{k-1} + bu_k \qquad (5)$$

Fuzzy membership function

The membership functions for phosphorus loadings and flow discharge are presented. The data were grouped to determine the relative frequency. The relative frequency is calculated by dividing the frequency in each interval by the highest frequency (Hong and Vincent, 1995).

From the Vollenweider model, the phosphorus (P) is represented by the membership function for phosphorus content and q is represented by the membership function for discharge. The membership function for the phosphorus loadings were determined by using the arithmetic operation (Dong and Shah, 1987) as shown below:

$$[a,b] \bullet [c,d] = [\min(ac, ad, bc, bd), \max(ac, ad, bc, bd)]$$

[a,b] represent the interval number in the membership function for phosphorus content, while [c,d] represent the interval number membership function for hydraulic loadings. The operation is carried out to find the core and support of the phosphorus loadings membership function.

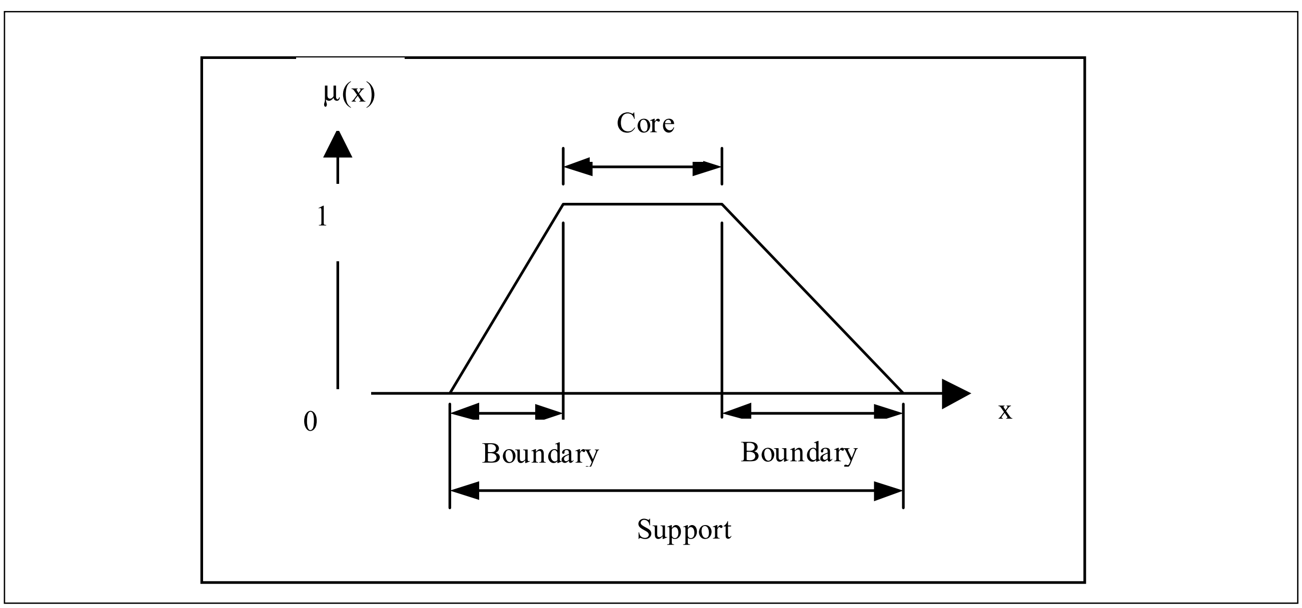

Figure 3. General feature of fuzzy membership function.

RESULTS

Data collection

The summary of phosphorus content and flow rates taken from site visits is shown in Table 1 and Table 2 respectively. Figure 4 and Figure 5 show the graphical representation of Table 1 and Table 2. Some of the data were not available due to flooding.

The highest phosphorus content recorded was 0.622 mg/l and the lowest concentration was 0.053 mg/l. The average phosphorus content was 0.214 mg/l. The highest value of streamflow recorded was 1.54 m^3/s during the first visit and the lowest value was 0.03 m^3/s.

Modeled results with IHACRES model

The rainfall and temperature data applied in the IHACRES model were from 1997 to 2006. The observed streamflow was obtained from Strategy Tegas Sdn. Bhd (2006) as shown in Table 3.

The highest value for annual streamflow was 1805 m^3/s from the year 2001 and the lowest value was 1093 m^3/s from the year 1997. The average annual streamflow was 1381 m^3/s. The highest average daily inflow was 4.95 m^3/s in 2001 and the lowest was 2.99 m^3/s. Supiah (2003) obtained slightly lower values using MIKE-11 modelling. The average and maximum values of streamflow obtained was 0.131 m^3/s and 2.618 m^3/s respectively. These values are slightly lower because MIKE-11 modeling takes into consideration many groundwater parameters.

The overall flow calibration using IHACRES for 1977-2006 is shown in Figure 6. The calibration parameters obtained are shown in Table 4. The flow calibration for 2003 is shown in Figure 7. Figures 8 and 9 show the modeling results for 2003 and 2006.

The statistical summary for model performance is shown in Table 5. The largest bias is -0.5546 mm/day and the smallest bias is -0.0076 mm/day. These values are close to zero and therefore it is acceptable. The highest R^2 value is 0.9925 while the lowest is 0.9208. An R^2 value nearer to 1

Table 1. Summary of phosphorus content from site visits in mg/l.

Station	Location	21/12/06	10/7/07	21/2/07	Note
1	Sungai Ban Foo	0.245	0.193	0.094	along the inflowing river
2	Sungai Ban Foo	0.224	0.231	0.172	along the inflowing river
3	Sungai Ban Foo	0.131	-	0.053	along the inflowing river
4	Sungai Ban Foo	0.236	-	0.184	within wetland area
5	Sungai Ban Foo	0.195	-	0.059	within wetland area
6	Sungai Ban Foo	0.237	-	0.574	within wetland area
7	Sungai Layang	0.292	-	0.074	along the inflowing river (at V-notch)
8	Sungai Layang	0.255	-	0.060	along the inflowing river
9	Sungai Layang	0.392	0.240	0.622	along the inflowing river (at fish breeding pond)
10	Sungai Layang	0.113	0.211	0.053	along the inflowing river (near fish breeding pond)

Table 2. Summary of flow rates from site visits in m^3/s.

Station	Location	21/12/2006	10/01/2007	21/02/2007
1	Sungai Ban Foo	1.54	0.25	0.06
2	Sungai Ban Foo	1.21	-	0.03
7	Sungai Layang	0.11	-	-
8	Sungai Layang	0.08	-	-

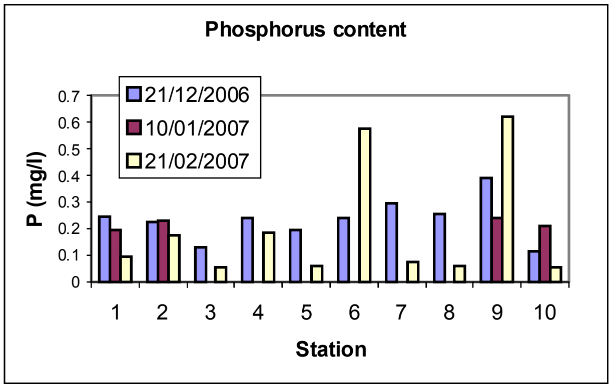

Figure 4. Phosphorus content in mg/l.

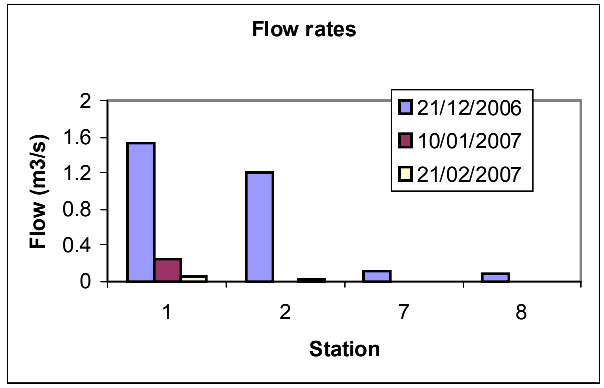

Figure 5. Flow rates in m^3/s.

Table 3. Summary of observed streamflow in m^3/s.

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Jan	7.73	29.55	99.12	161.31	284.42	99.07	190.83	252.24	170.7	262.59
Feb	246.07	23.05	17.09	94.01	56.56	17.09	69.07	3.07	0.00	42.57
Mar	100.34	99.14	29.95	141.15	162.07	29.95	84.31	220.18	43.18	76.72
Apr	297.04	58.84	216.93	72.16	227.56	216.93	130.66	74.06	40.47	135.55
May	40.40	89.99	139.75	72.99	121.16	139.75	60.32	68.61	206.43	232.91
Jun	77.42	231.24	190.64	127.98	81.75	190.64	34.42	100.91	54.45	82.66
Jul	57.62	95.04	108.94	151.37	40.52	108.94	99.18	136.12	141.37	75.45
Aug	67.7	132.91	60.38	59.45	81.75	60.38	168.76	155.42	61.92	58.91
Sep	2.07	118.89	77.05	6.30	243.01	77.05	160.05	140.05	149.59	14.14
Oct	52.29	86.45	52.98	78.65	60.01	52.98	154.54	107.88	175.02	29.29
Nov	54.98	37.70	97.07	58.27	124.74	97.07	120.57	175.39	151.46	73.39
Dec	90.15	259.13	164.61	207.73	321.56	164.61	113.83	68.67	53.54	692.49
Total	1093.81	1261.93	1254.51	1231.37	1805.11	1254.46	1386.54	1502.6	1248.13	1776.67

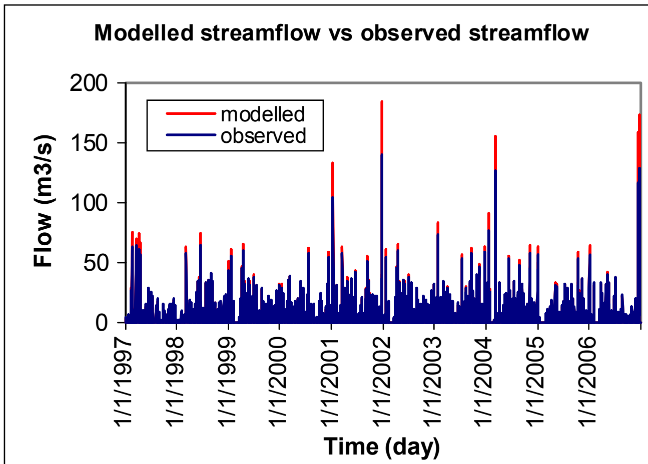

Figure 6. Modelled daily streamflow vs observed streamflow for 1997-2006.

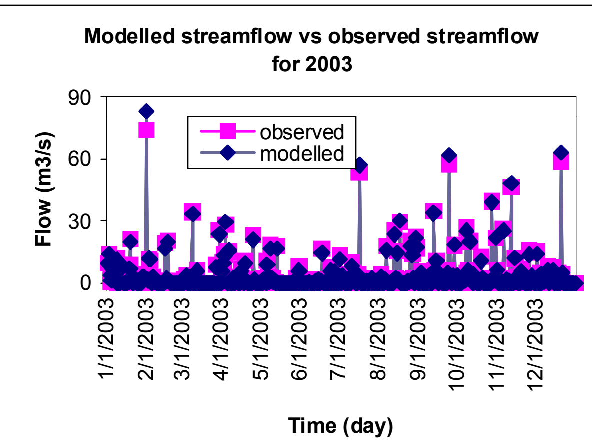

Figure 7. Modelled daily streamflow vs daily observed streamflow for 2003.

indicates the better performance of the model. Both statistics showed that the model is able to perform well.

Fuzzy membership function

The boundaries for the phosphorus content membership function are 0.05 mg/l, 0.1 mg/l, 0.3 mg/l and 0.77 mg/l (Figure 10). The boundaries for the hydraulic loadings membership function

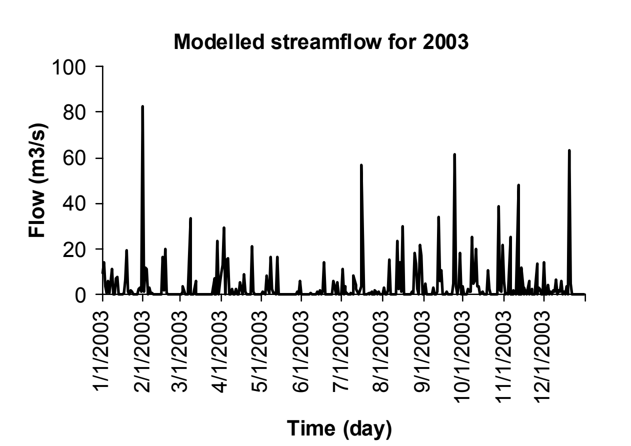

Figure 8. Modelled daily streamflow for 2003.

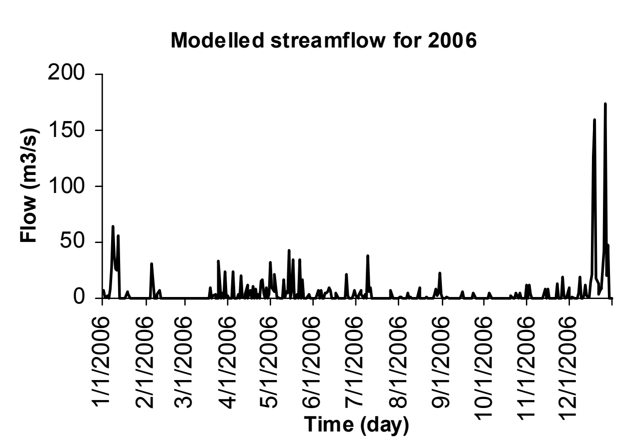

Figure 9. Modelled daily streamflow for 2006.

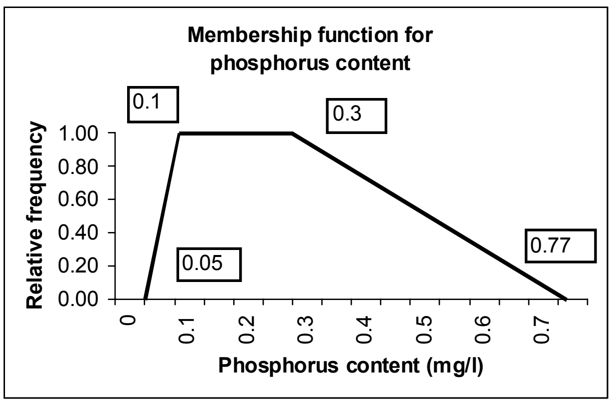

Figure 10. Membership function for phosphorus content

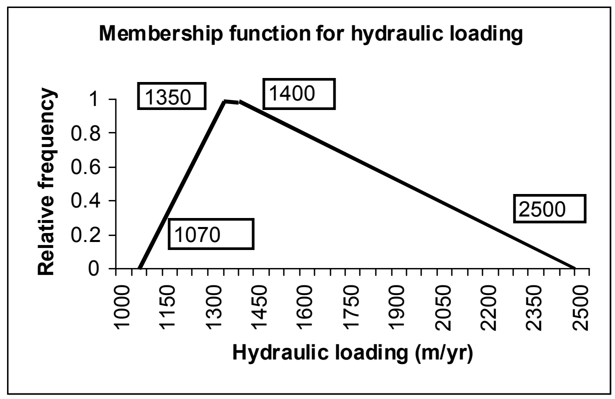

Figure 11. Membership function for hydraulic loadings

Table 4. Parameters for optimal calibration

Drying rate at reference temperature (tw)	4.0
Temperature dependence of drying rate (f)	0.0
Reference temperature (tref)	26.0
Moisture threshold for producing flow (l)	0.0
Power on soil moisture (p)	0.2

Table 5. Statistical summary of model performance.

Period	Bias (mm/d)	R squared
1997	-0.0076	0.9764
1998	0.0171	0.9866
1999	0.0574	0.9925
2000	0.2839	0.9916
2001	-0.2840	0.9457
2002	0.2382	0.9918
2003	0.2284	0.9918
2004	0.0420	0.9733
2005	0.0389	0.9896
2006	-0.5546	0.9208

are 1070 m/yr, 1350 m/yr, 1400 m/yr and 2500 m/yr (Figure 11).

In the membership function, the most likely conditions are met when the membership value is closer to 1. The estimated range for phosphorus loadings was from 0.26 g/m^2/yr to 0.81 g/m^2/yr (7.81 ton/yr to 24.28 ton/yr) as shown in Figure 12. Green and Brian (1997) obtained 257 tons/year of phosphorus from a very much larger watershed of the Illinois River. Tanic et al. (1998) obtained 13 kg/day (approximately 4 tonnes/year) from 311 km^2 of the Lake Sapanca catchment, Turkey. This value was slightly smaller mostly because of lower rainfall (600-1000 mm/year) in Lake Sapanca. Larsen et al. (1999) obtained 15.65 ton/yr of phosphorus from an average of 879.66 km^2 of agricultural watershed in Denmark in 1996. Chiew and McMahon (1999) stated that pollution load can vary considerably between catchments, and in the absence of local event water quality data, his tabulation of EMC data summaries can be used as a guide to estimate the probable range of diffuse pollution load generated from a catchment.

The average phosphorus content is 0.214 mg/l and average hydraulic loading is 1452.25 m/yr. The average calculated phosphorus loading is 0.6 g/m^2/yr. From Figure 11, the degree of membership for 0.6 g/m^2/yr is 1, which means it is most likely to occur. The value of 0.6 g/m^2/yr is also within the estimated range of 0.26 g/m^2/yr to 0.81 g/m^2/yr.

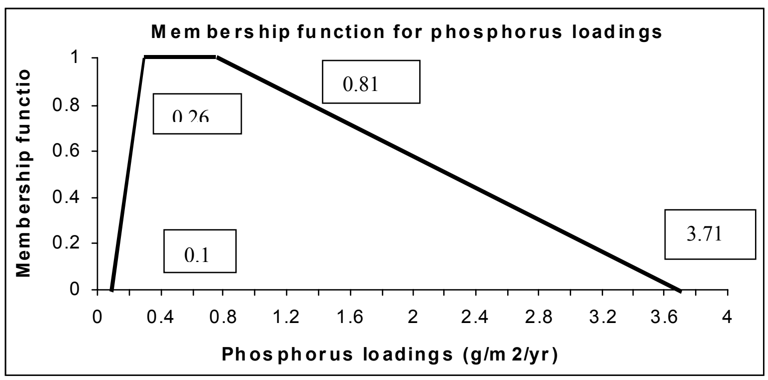

Figure 12. Membership function for phosphorus loadings.

CONCLUSIONS

The conclusions from this study are as follows:

i) The estimated most likely phosphorus loading is 0.26 g/m^2/yr to 0.81 g/m^2/yr (7.81 ton/yr to 24.28 ton/yr) using the Vollenweider model.

ii) The IHACRES model is able to perform well based on the bias and R^2 values obtained from the simulation. The largest bias is -0.5546 mm/day and the smallest bias is -0.0076 mm/day. The highest R^2 value is 0.9925 while the lowest is 0.9208.

iii) The fuzzy membership function is implemented to represent the uncertainty of the phosphorus loading estimation. The range of minimum and maximum values for certain parameters of the Vollenweider model can be obtained through the use of the fuzzy membership function.

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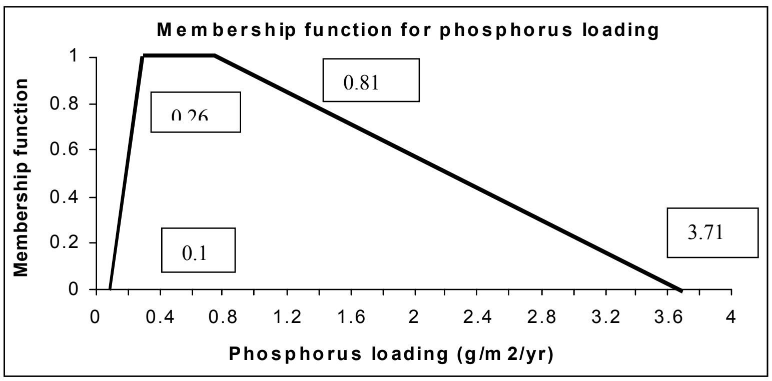

Figure 12. Membership function for phosphorus loadings