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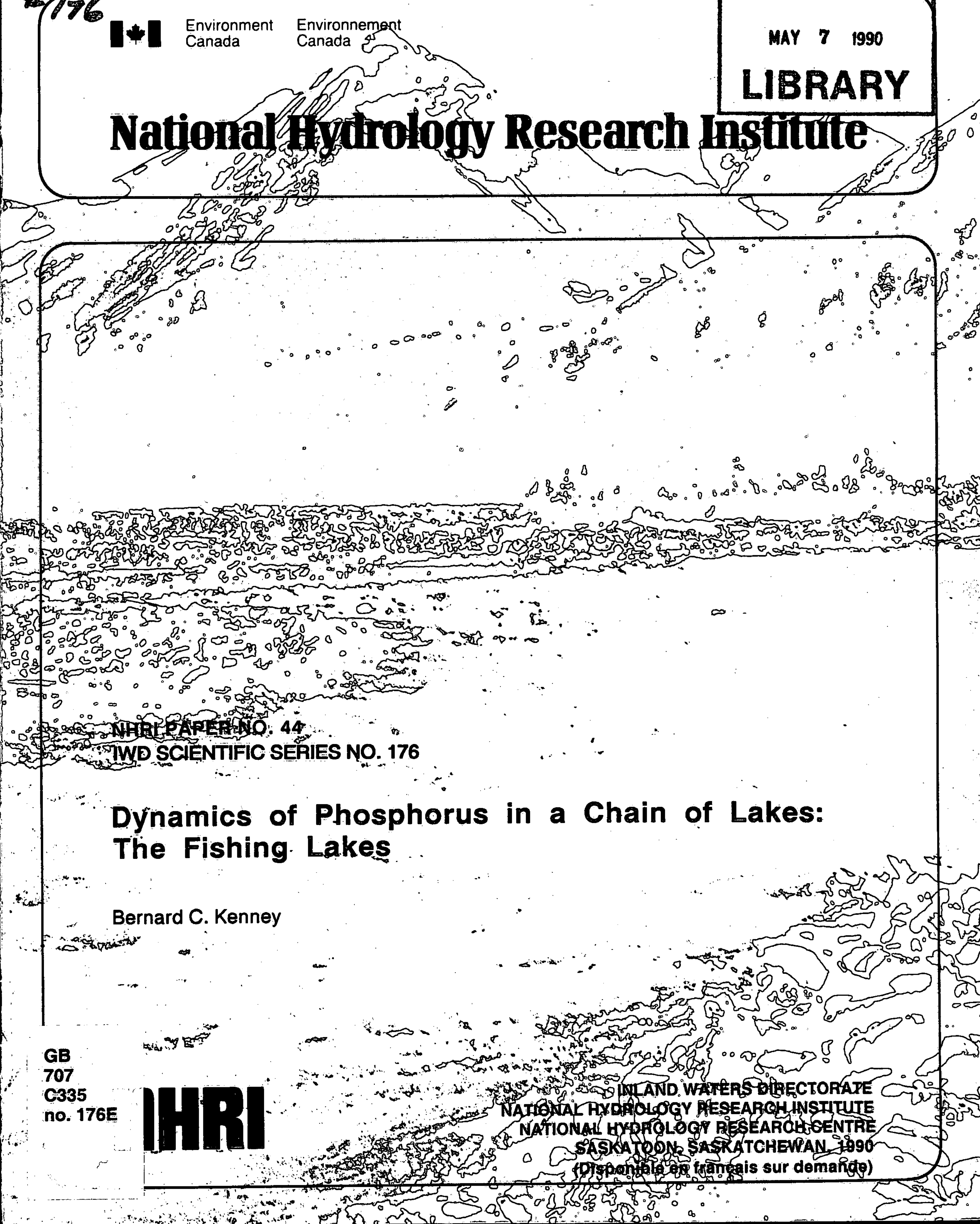

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Dynamics of Phosphorus in a Chain of Lakes: The Fishing Lakes

Bernard C. Kenney

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Abstract

Lake phosphorus concentrations fluctuate as a forced response to changes in inflow phosphorus. The theory of lake phosphorus dynamics has been extended to describe phosphorus concentrations in the outflow from a chain of four large prairie lakes. The simulation of phosphorus concentrations in the Fishing Lakes must take into account high prairie evaporation, precipitation, and varying lake levels. Using inflow data collected at 3-day intervals from 1980 to 1983, together with all other available data collected at random times from 1970, the phosphorus concentration in the outflow from the Fishing Lakes was numerically simulated and compared with measured values.

The Fishing Lakes are saturated with phosphorus. No net sedimentation of phosphorus occurs in the lakes although there is a reduction of particulate TP and an increase in dissolved TP in the outflow. The dynamic response of the Fishing Lakes is determined largely by the outflow time scale, which was generally longer than the length of the data record. During the spring floods of 1974, 1975, 1976, and 1982, the outflow time scale was sufficiently small to allow a change in the lake TP during the period of the record, but only the 1974 flood was accompanied by a reduction in the inflow TP. The simulated lake phosphorus dropped over 100 mg/m^3 to about 350 mg/m^3 during the flood and has remained at about that level since 1974. The measured P_L is noisier, but it also shows that a marked decrease accompanied the 1974 flood. On the other hand, there has been no detectable response in the Fishing Lakes to the tertiary treatment of Regina sewage.

Résumé

Les concentrations de phosphore dans les eaux lacustres fluctuent en fonction des apports de phosphore dans le volume entrant. La théorie de la dynamique du phosphore dans les eaux lacustres a été étendue de façon à décrire les concentrations de phosphore dans le volume sortant d'une chaîne de quatre lacs de grande superficie situés dans les Prairies. On doit tenir compte du taux élevé d'évaporation dans les Prairies, des précipitations et des niveaux variables des lacs. En utilisant les données sur le volume entrant obtenues à des intervalles de trois jours entre 1980 et 1983, ainsi que toutes les autres données disponibles obtenues au hasard depuis 1970, on a fait une simulation numérique de la concentration de phosphore dans le volume sortant des lacs Fishing et on a comparé les valeurs ainsi obtenues avec les valeurs mesurées.

Les eaux des lacs Fishing sont saturées de phosphore. Il n'y a pas de sédimentation nette de phosphore dans les lacs, bien qu'il y ait diminution du PT particulaire et augmentation du PT dissous dans le volume sortant. La réponse dynamique des lacs Fishing est en grande partie déterminée par le temps de renouvellement des eaux qui, en général, était plus long que la période pour laquelle des données étaient disponibles. Au cours des crues printanières de 1974, 1975, 1976 et 1982, le temps de renouvellement était suffisamment court pour que le PT dans les eaux lacustres subisse un changement pendant la période pour laquelle des données étaient disponibles, mais seule la crue de 1974 était accompagnée d'une diminution des apports de PT. Selon la simulation, la concentration de phosphore dans les eaux lacustres a, au cours de la période de crue, chuté de plus de 100 mg/m^3 pour atteindre une valeur d'environ 350 mg/m^3 ; cette concentration est restée à peu près la même depuis 1974. La valeur mesurée de la concentration de phosphore dans les eaux lacustres (P_L) présente de plus grandes fluctuations aléatoires, mais elle accuse également une diminution notable au cours de la période de crue de 1974. D'autre part, il n'y avait aucune réponse décelable des lacs Fishing au traitement tertiaire des eaux usées de Regina.

Management Perspective

Saskatchewan's Fishing Lakes, the primary recreation lakes for residents of Regina, are plagued by immense blooms of algae throughout the summer. The algae thrive on high concentrations of nutrients, particularly phosphorus. The dynamics of phosphorus in lakes are normally controlled by water renewal rates and sedimentation. In this report, the theory of phosphorus dynamics was extended to include a chain of lakes like the Fishing Lakes. Model results using all available data from 1970 suggest that the Fishing Lakes are saturated with phosphorus and that no net sedimentation of phosphorus is occurring. No response in lake phosphorus was found that could be attributed to tertiary treatment of Regina sewage. To define the phosphorus dynamics in the Fishing Lakes more thoroughly requires a better data base (e.g., accurate monthly data over a period of time that is 3 to 5 times longer than the mean water renewal time).

Dynamics of Phosphorus in a Chain of Lakes: The Fishing Lakes

Bernard C. Kenney

INTRODUCTION

A federal-provincial agreement (Qu'appelle Basin Agreement) was signed in 1970 to create "a comprehensive framework plan for the development and management of water resources for social betterment and economic growth in the Qu'Appelle basin." Studies were initiated under this agreement to identify and analyse a broad range of existing and potential water use and water quality problems and to evaluate various management alternatives for resolving these problems. Sixty-four recommendations were made (Qu'Appelle Basin Study Board, 1972) encompassing aspects of water quality, water supply, land and water surface use, and flood hazard in the Qu'Appelle basin. The water quality recommendations emphasized that nutrient reduction from municipal sewage, cottage wastes, and agricultural and livestock practices was essential for improved water quality and the control of algae. Additional research into the role of lake sediments on nutrients was also recommended.

The Qu'Appelle Implementation Board was formed to carry out the extensive recommendations of the study. In order to reduce nutrient inputs from municipal sewage, a tertiary treatment plant was constructed in Regina, which began operation in June 1976. A study of the effectiveness of the tertiary treatment plant on the water quality in Wascana Creek was conducted by Tones (1981).

Evaluation of the impact of the tertiary treatment plant on the Fishing Lakes is hampered by the lack of continuous historic data on nutrients in the Qu'Appelle basin prior to the start of tertiary treatment. Available data have been acquired from limited monitoring of the rivers and from various special programs through the years, but changes in sampling sites, sampling frequency, and analytical techniques reduce the usefulness of the existing data base for identifying trends. Following a detailed examination of the nutrient data base available at the time, Cross (1978) concluded that the rivers were sampled too infrequently for a thorough nutrient budget study and that very little reliable data existed on the Fishing Lakes themselves.

To augment ongoing monitoring, a Water Quality Branch (WQB) program of intensive (3-day) sampling was begun in April 1980 to evaluate the effectiveness of the treatment plant in reducing phosphorus loading to the Fishing Lakes. Another objective of the sampling program was to estimate recent trends in the nutrient quality, loading, and productivity of the Qu'Appelle River upstream and downstream from the Fishing Lakes (Water Quality Branch, 1982a, 1982b). The WQB sampling program was originally proposed to run 5 years, but its implementation was delayed until 1980, and the program was prematurely terminated in the spring of 1983 when the Qu'Appelle Implementation Agreement expired.

The present report examines aspects of the dynamics of phosphorus in the Fishing Lakes using both the WQB (3-day) data and all available prior data. A thorough understanding of phosphorus dynamics in prairie lake systems is important for rational evaluation of lake management alternatives and for the assessment of large-scale engineering perturbations.

The theoretical basis for this work was developed following an evaluation of the nutrient loading concept and the nutrient loading diagrams used to predict changes in lake eutrophication (Kenney, 1982, 1990a). The dynamics of phosphorus in lakes were also examined in Kenney (1990a), and it was shown that the dynamic response of a lake to changes in inflow phosphorus depended solely on a few characteristic time scales of the lake. A model was then developed based on two time scales: the water renewal or outflow time scale and the sedimentation time scale. This two-time-scale model was successfully applied to the recovery of Lake Washington following sewage diversion (Kenney, 1990b). The theory is extended herein to simulate the phosphorus dynamics of a chain of lakes. Because large differences exist between water inflow and outflow in the Fishing Lakes, with concomitant variations in lake level, the theory is further expanded to a three-time-scale model by the addition of the water inflow time scale. The dynamic variation of phosphorus in the Fishing Lakes from 1980 to 1983 was then simulated using the phosphorus inflow concentrations measured every 3 days by WQB and the daily water flows as input data. A second simulation was run using the sparse data set that was available for phosphorus inflow from 1970 to 1979. The calculated outputs were directly compared with the measured outflow concentrations.

THE FOUR FISHING LAKES OF THE QU'APPELLE VALLEY

Pasqua, Echo, Mission, and Katepwa lakes form a chain in the glacial meltwater Qu'Appelle Valley in southern Saskatchewan about 125 m below the level of the surrounding plain (Fig. 1). The Qu'Appelle River drains 36 600 km^2 upstream from the lakes, much of it in agricultural use as cropland and rangeland. Sewage from the cities of Regina and Moose Jaw and from other smaller communities also enters the drainage basin. In 1972, it was estimated that 56% of the total phosphorus (TP) input to the Qu'Appelle basin was from Regina and 13% was from Moose Jaw (Qu'Appelle Basin Study Board, 1972). Cullimore and Johnson (1971) calculated that 44% of the TP input to Pasqua Lake came from Regina.

All four lakes are highly eutrophic and produce immense blooms of blue-green algae. Background details of the physics and chemistry of the lakes are reported with results of previous work on the eutrophication of the Fishing Lakes by Hammer (1971, 1973). A comprehensive description of the geology of the valley and a theory to explain the origin of the Fishing Lakes are presented by Christiansen et al. (1977).

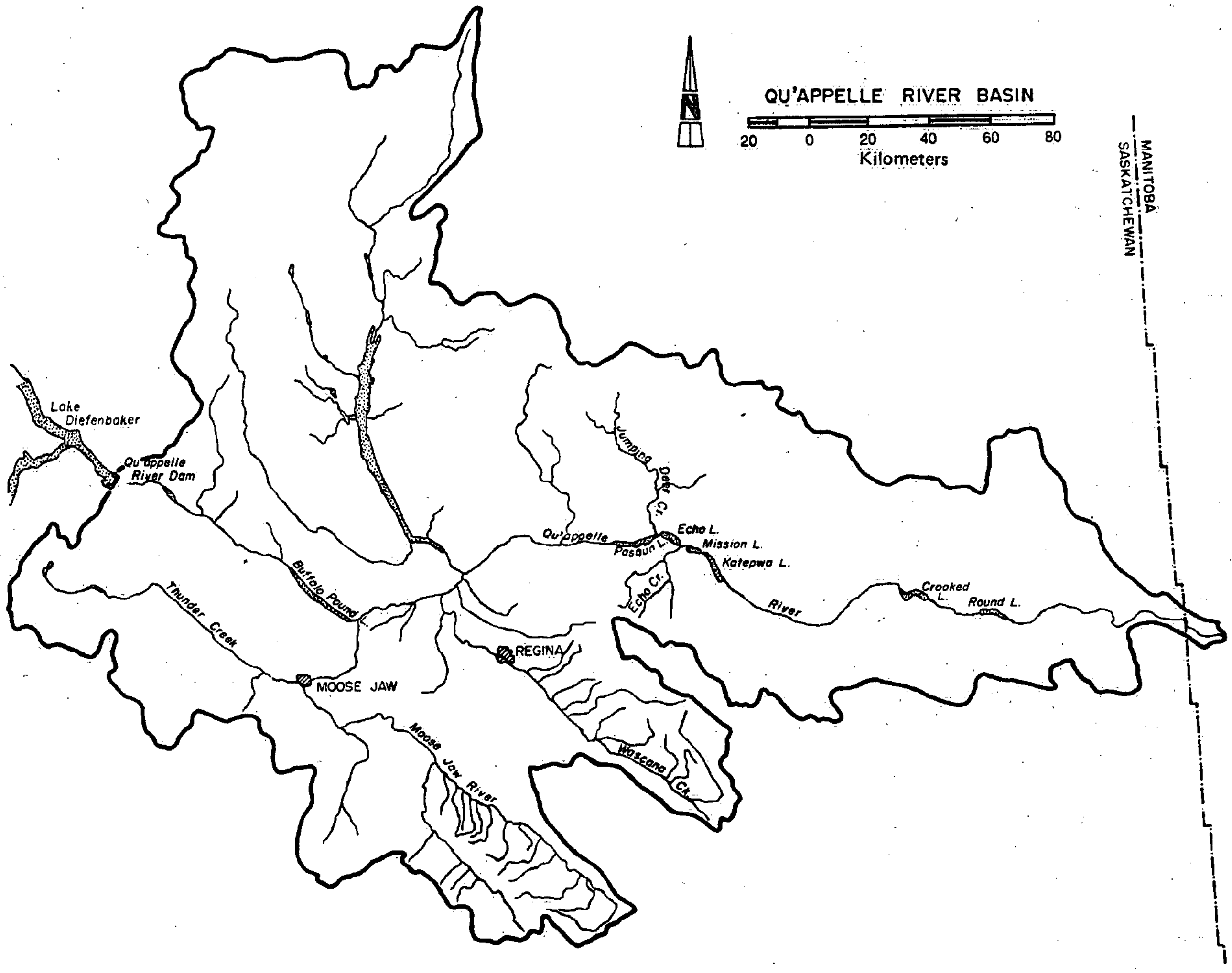

Figure 1. Qu'Appelle River basin showing the location of Pasqua, Echo, Mission, and Katepwa lakes, also known as the Fishing Lakes.

LAKE PHOSPHORUS DYNAMICS

A time-dependent model of the dynamics of phosphorus in lakes was developed in Kenney (1990a, 1990b) for lakes with a single inflow and outflow. It was assumed that the water inflow and outflow were equal so that the dynamic response of the lake was totally characterized by the water renewal time scale. The model had one source of phosphorus, the inflow concentration, and one sink, flushing of phosphorus out the outflow. It was shown that the steady state lake phosphorus concentration equalled the inflow concentration and that the time required to reach steady state was equal to 5 times the water renewal time.

Another model was then considered, which had a second phosphorus sink, sedimentation. The starting point for the analysis was the equation describing the rate of change of phosphorus in a lake:

$$\frac{dP_L}{dt} = \underset{\text{(source)}}{\frac{P_iQ}{Az}} - \underset{\text{(sink)}}{\frac{P_LQ}{Az}} - \underset{\text{(sink)}}{\sigma P_L} \qquad (1)$$

where P_L is the lake phosphorus concentration,
P_i is the inflow concentration,
Q is the water flow through the lake,
A is the surface area of the lake,
z is the mean depth, and
σ is the sedimentation constant.

In this case, the lake was totally described by two time scales: the water renewal time scale as before and the sedimentation time scale. It was shown that the steady state lake phosphorus concentration was always less than the inflow concentration for lakes with sedimentation. Both time scales were allowed to be time dependent and the lake phosphorus concentration was simulated as subjected to the forcing produced by changing inflow concentrations. Using a time history of measured inflow concentrations and discharge, the lake concentration in Lake Washington was successfully simulated.

Phosphorus Dynamics in a Chain of Lakes

The Fishing Lakes differ from Lake Washington in several respects that influence the application of dynamic models. The most obvious physical difference is the sequence of four independent lakes in a large river valley. The dynamic behaviour of a chain of lakes is now derived and compared with that of a single large lake with the same total volume.

Equation (1) may be independently applied to several lakes in a chain where the outflow from one lake represents the inflow to the next lake in the chain. If P_{iP} is the inflow concentration to Pasqua Lake and P_{LP} is the lake concentration of Pasqua Lake, then P_{LP} is also the outflow concentration from Pasqua (because the model assumes each lake is well mixed) as well as the inflow concentration to Echo Lake. Similarly, P_{LE} represents both the Echo Lake concentration and the inflow to Mission Lake, P_{LM} represents both the Mission Lake concentration and the inflow to Katepwa Lake, and P_{LK} represents the Katepwa Lake concentration and the outflow from the chain.

The outflow from the lake chain may be found by simultaneous solution of four equations like equation (1) above. Assuming the flow through the lakes is Q and the volumes of the lakes are V_P, V_E, V_M, and V_K, then

$$\frac{dP_{LP}}{dt} = \frac{P_iQ}{V_P} - \frac{P_{LP}Q}{V_P} - \sigma_P P_{LP} \qquad (2)$$

$$\frac{dP_{LE}}{dt} = \frac{P_{PL}Q}{V_E} - \frac{P_{LE}Q}{V_E} - \sigma_E P_{LE} \qquad (3)$$

$$\frac{dP_{LM}}{dt} = \frac{P_{LE}Q}{V_M} - \frac{P_{LO}Q}{V_M} - \sigma_M P_{LM} \qquad (4)$$

$$\frac{dP_{LK}}{dt} = \frac{P_{LM}Q}{V_K} - \frac{P_{LK}Q}{V_K} - \sigma_K P_{LK} \qquad (5)$$

represent the rate of change of phosphorus concentration in the Fishing Lakes. When the variation in P_i, Q, and the V's and σ's are known, the temporal variations in lake concentrations can be found.

For the case of a sudden increase in inflow concentration, each of the above equations has a solution of the form

$$\frac{P_L}{P_i} = \frac{1 - \exp(-t/\tau)\exp(-\sigma t)}{1 + \sigma\tau} \qquad (6)$$

Therefore, the outflow from the nth lake in a chain of n lakes can be expressed by the product of n terms,

$$\frac{P_{Ln}}{P_i} = \prod_{1}^{n} \frac{1 - \exp(-t/\tau_n)\exp(-\sigma_n t)}{1 + \sigma_n\tau_n} \qquad (7)$$

Figure 2 shows the simulated outflow concentration from Katepwa Lake following a sudden increase in inflow concentration to Pasqua Lake using a Q typical of a high flow year and a sedimentation time scale of 1 year. The response of a single large lake with the same total volume as the four Fishing Lakes is also shown. There is a delayed

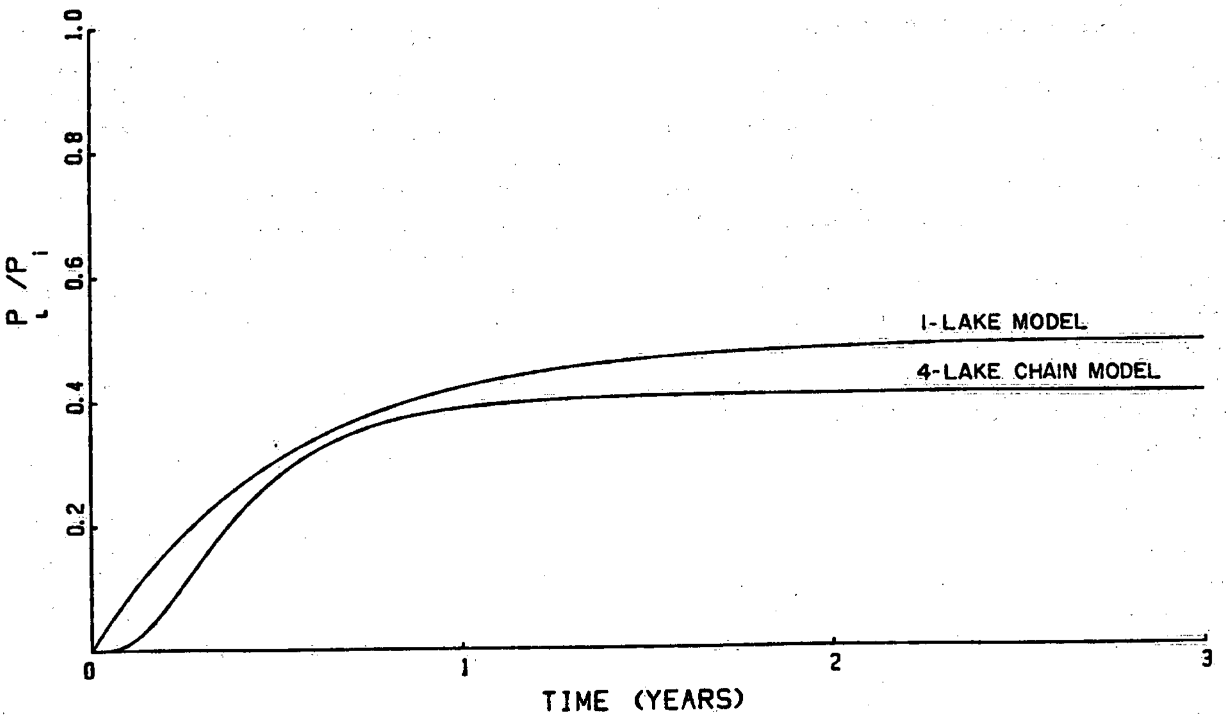

Figure 2. Step function response of a four-lake chain with sedimentation compared with a single lake of the same total volume.

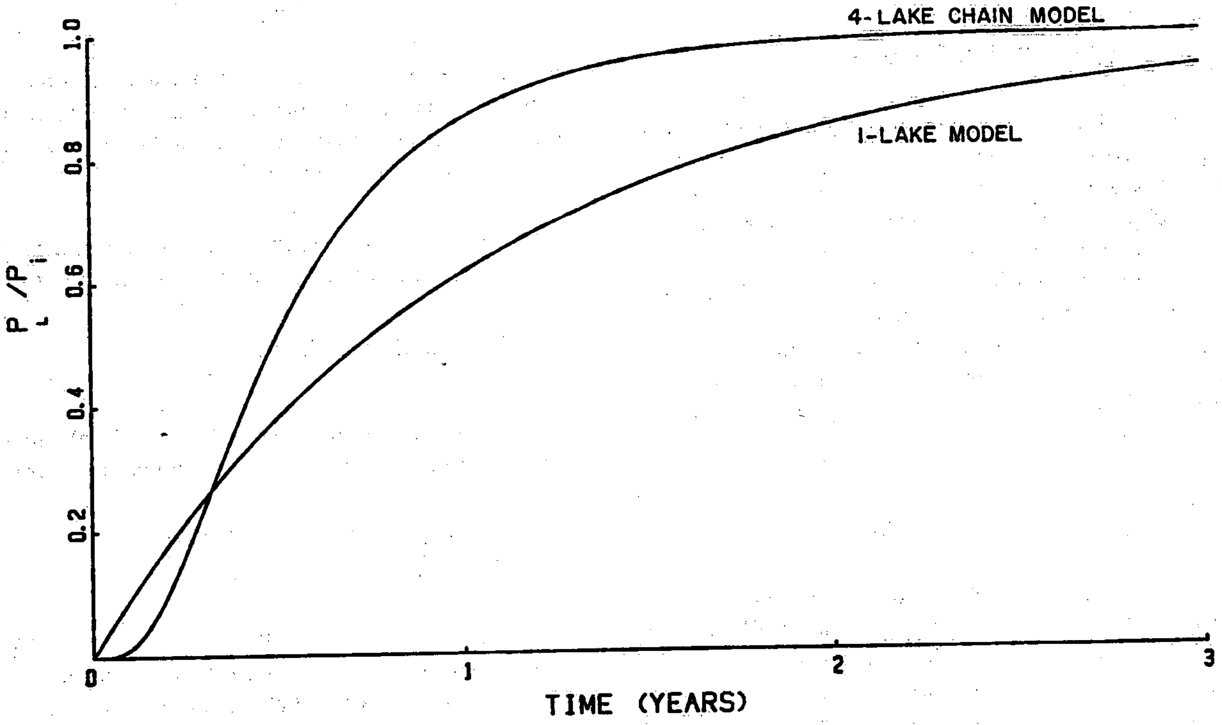

Figure 3. Step function response of a four-lake chain with no sedimentation compared with a single lake with the same total volume.

initial response in the chain of lakes. Once the outflow of the chain begins to respond, however, it does so more rapidly so that the steady state outflow concentration is actually reached sooner in spite of the initial delay. The steady state concentration is lower downstream from a chain of lakes relative to a single lake with the same total volume as long as there are sedimentation losses.

An example of four lakes similar to the Fishing Lakes in a high flow year, but with no sedimentation losses, is shown in Figure 3. Once again there is a delayed initial response in the outflow from a chain of lakes relative to that of a single lake of the same total volume. When the lake chain begins to respond, however, it does so more rapidly. With no sedimentation, the steady state outflow of both lake systems is simply equal to the inflow concentration.

Thus it has been shown that a chain of lakes and a large single lake with the same total volume are different with respect to both the frequency response and the scaling of lake phosphorus concentrations. Quantitatively, the differences depend upon the values of the water renewal and sedimentation time scales for each lake system.

The lake chain analysis may also be used for a quantitative assessment of the well-mixed assumption for a large lake. By dividing the large lake into numerous small basins that are well-mixed, the subbasins may be treated like a chain of smaller lakes. Incomplete mixing in a large lake, therefore, is expected to introduce a delayed response at the outflow, but a faster overall response time than a geometrically similar well-mixed lake. In a large lake with a sedimentation sink, the incompletely mixed lake would also have lower steady state concentrations than the well-mixed lake of the same volume.

A Three-time-scale Model for the Fishing Lakes

Application of the principles of phosphorus dynamics to the Fishing Lakes requires further analytical extension to the above models to account for the differences in the water budgets. In the Fishing Lakes, there appears to be substantial water loss due to evaporation. While evaporation can be important to the water budget, it does not contribute to the phosphorus budget. The source of phosphorus entering the lake is proportional to the water inflow, and the flushing sink is proportional to the water outflow from the lake. The model equation describing lake phosphorus concentrations is now

$$\frac{dP_L}{dt} = \underset{\text{(source)}}{\frac{P_iQ_i}{Az}} - \underset{\text{(sink)}}{\frac{P_LQ_o}{Az}} - \underset{\text{(sink)}}{\sigma P_L} \qquad (8)$$

where Q_i is the water inflow to the lake,

Q_o is the water outflow from the lake,

and the other variables are the same as before.

This model has three time scales: the inflow time scale $\tau_i = Q_i/Az$, the outflow time scale $\tau_o = Q_o/Az$, and the sedimentation time scale $\tau_s = 1/\sigma$ as before. Equation (8) can be solved by separation of variables. The solution subject to the initial condition $P_L = 0$ when $t = 0$ is

$$\frac{P_L}{P_i} = \frac{1}{\frac{\tau_i}{\tau_o} + \frac{\tau_i}{\tau_s}} [1 - \exp(-t/\tau_o)\exp(-t/\tau_s)] \qquad (9)$$

It is readily apparent that equation (9) reverts to the two-time-scale result in Kenney (1990a) when $\tau_i = \tau_o$.

Note that the inflow time scale does not directly influence the frequency response of the lake, but only the scaling. For example, consider a lake with no sedimentation and where half the water inflow is lost due to evaporation from the lake surface. Then, $\tau_i = \tau_o/2$ and the steady state value of $P_L = 2P_i$ from equation (9). Since no TP is lost with the evaporated water, the lake evaporation concentrates the phosphorus that enters the lake with the inflow. Unlike the one- and two-time-scale models presented in Kenney (1990a), P_L/P_i can now exceed 1 at steady state. Alternatively, if a second lake with the same τ_o were being diluted with phosphorus-free water such that $\tau_i = 2\tau_o$, then $P_L = P_i/2$ at steady state with no sedimentation, as expected. The time required to reach steady state, however, is the same for both lakes even though the inflow time scales differ by 4.

The ratio τ_o/τ_i can be considered a lake concentration factor. When the lake concentration factor is greater than 1, the lake concentration will exceed the input concentration by this ratio. Similarly, when the ratio is less than unity, the input concentration will be diluted by this ratio.

The effects of the lake concentration factor are similar for lakes with sedimentation. P_L/P_i may still exceed 1, but only if the effects of the concentration factor exceed the losses due to sedimentation.

Phosphorus Loading

Before applying the results of the above analysis to the Fishing Lakes, some comment on the widespread use of the phosphorus loading concept is necessary. Phosphorus loading is most commonly defined as the product of the phosphorus concentration and the discharge. While the dynamics of phosphorus in a lake can be readily formulated in terms of the phosphorus loading to the lake, L_i, and phosphorus loading from the lake, L_o (by substitution of L_i for P_iQ_i and L_o for P_LQ_o in equation [8]), the resulting equation cannot be solved if only the loadings are known. The reason is the information loss that accrues when computing loading (as the product of concentration and discharge). Moreover, it is clearly shown in this paper that lake phosphorus concentration scales with the inflow concentration (and not with the loading to the lake). Since the concentration and the discharge must both be known in order to compute the loading, there is little to be gained by the use of this concept for dynamic environments. On the other hand, substantial error can be introduced when simply comparing loadings to and from a lake because such a procedure involves the implicit assumption that the lake is in steady state. A detailed evaluation of the phosphorus loading concept was given by Kenney (1990a).

WATER BUDGET OF THE FISHING LAKES

The water budget of the Fishing Lakes has been estimated by Cross (1978) and others, usually on the basis of annual average data. In order to model the nutrient dynamics of the four Fishing Lakes separately, it is necessary to have inflow and outflow data from each lake. Since the Water Survey of Canada (WSC) only measures the flow upstream and downstream from the four lakes, the water budget of the lake system was examined on the basis of daily averaged data to determine the feasibility of calculating the inflows to and outflows from the individual lakes.

The discharge of the Qu'Appelle River to the Fishing Lakes is shown in Figure 4 along with the outflow to the river below Katepwa Lake for the period of the 72-hour sampling program of WQB. Both 1980 and 1981 were low flow years, while 1982 was considered a moderate flow year.

The difference between the inflow and the outflow shown in Figure 5 was found to be of the same order as the flows themselves. The flow deficit in the fall of 1980 was caused by manipulation of the control structure between Echo and Mission lakes to reduce the flood threat the following spring. The reduction in the volume of the two upper lakes may be seen in Figure 6. Simultaneously, there was a slight increase in the volume of both Mission and Katepwa lakes. A similar draw down of the upper lakes occurred in the fall of 1981 and 1982, although the flow deficit was much less than for 1980 (Fig. 6).

The impact of lake level manipulation on the total volume of the four Fishing Lakes was less obvious (Fig. 7) because of the inverse correlation between the two upper and two lower lakes.

In its simplest form, the water budget of the Fishing Lakes can be expressed as

$$\text{Inflow} - \text{Outflow} = \text{Change in lake volume} = dV$$

The change in lake volume was calculated from measurements of lake level made in Echo and Katepwa lakes since the two upper and two lower lakes are directly connected. Lake capacity charts calculated by the Prairie Farm Rehabilitation Administration (PFRA) were used to relate lake levels to volumes.

The Qu'Appelle River is the only large river system feeding the Fishing Lakes. There are about a dozen minor tributaries that flow directly to the lakes, the largest two being Jumping Deer and Echo creeks. The drainage basin upstream from the lakes is about 36 600 km^2. The local drainage basin including Jumping Deer and Echo creeks is only 4000 km^2. For randomly distributed rainfall and runoff proportional to the size of the drainage basin, the inflow is expected to be dominated by the Qu'Appelle River. Other inflows are direct precipitation to the surface of the lakes plus any ground-water inflow. Direct precipitation can be estimated on an annual basis from rain gauge data available from the vicinity of the Fishing Lakes (Cross, 1978). Rainfall is reported on a daily basis so that it is possible to estimate the daily precipitation on the surface of the lakes with reasonable accuracy.

Ground-water inflow is more difficult to estimate quantitatively. Numerous springs emerge from the sides of the valley to visibly contribute ground water to the lakes. These are particularly common along the south shore of Echo Lake.

There is also a persistent belief that there is a significant ground-water inflow directly at the bottom of the Fishing Lakes. The belief is supported by local geology since a large aquifer, the Hatfield Valley aquifer, is known to run across the valley at a depth of about 40-50 m below the Fishing Lakes (Christiansen et al., 1977). A previous study was made of major aquifers in the Qu'Appelle Valley by Rey (1970). The deep holes in the bottom of the Fishing Lakes are believed to be caused and maintained by direct ground-water flow from this aquifer. There are, however, no observation wells in the Fishing Lakes area to provide a direct indication of seasonal variation in the ground-water flow to the lakes. A plot of daily fluctuations of the water table during 1971 from a well 130 km northwest of Katepwa Lake was presented by Christiansen et al. (1977) as typical of the Qu'Appelle region. These results suggest

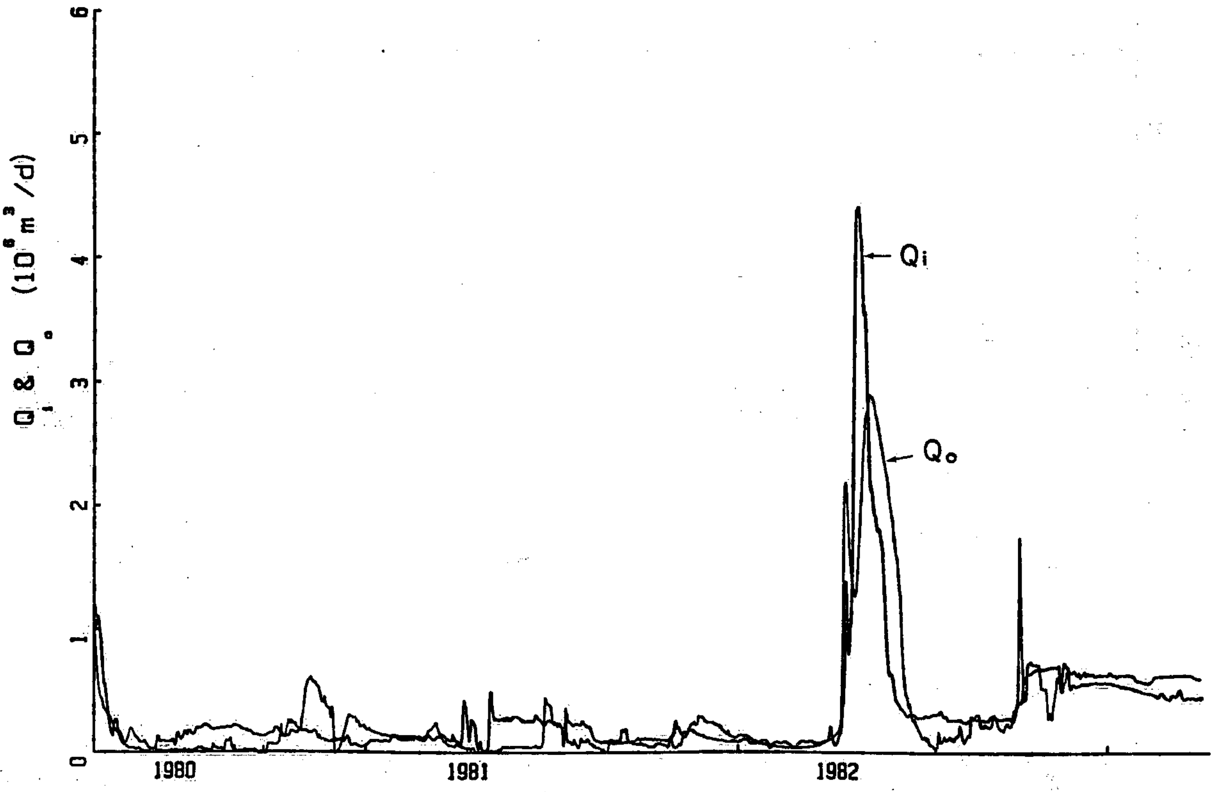

Figure 4. The inflow to (Q_i) and outflow from (Q_o) the Fishing Lakes chain from 1980 to 1983.

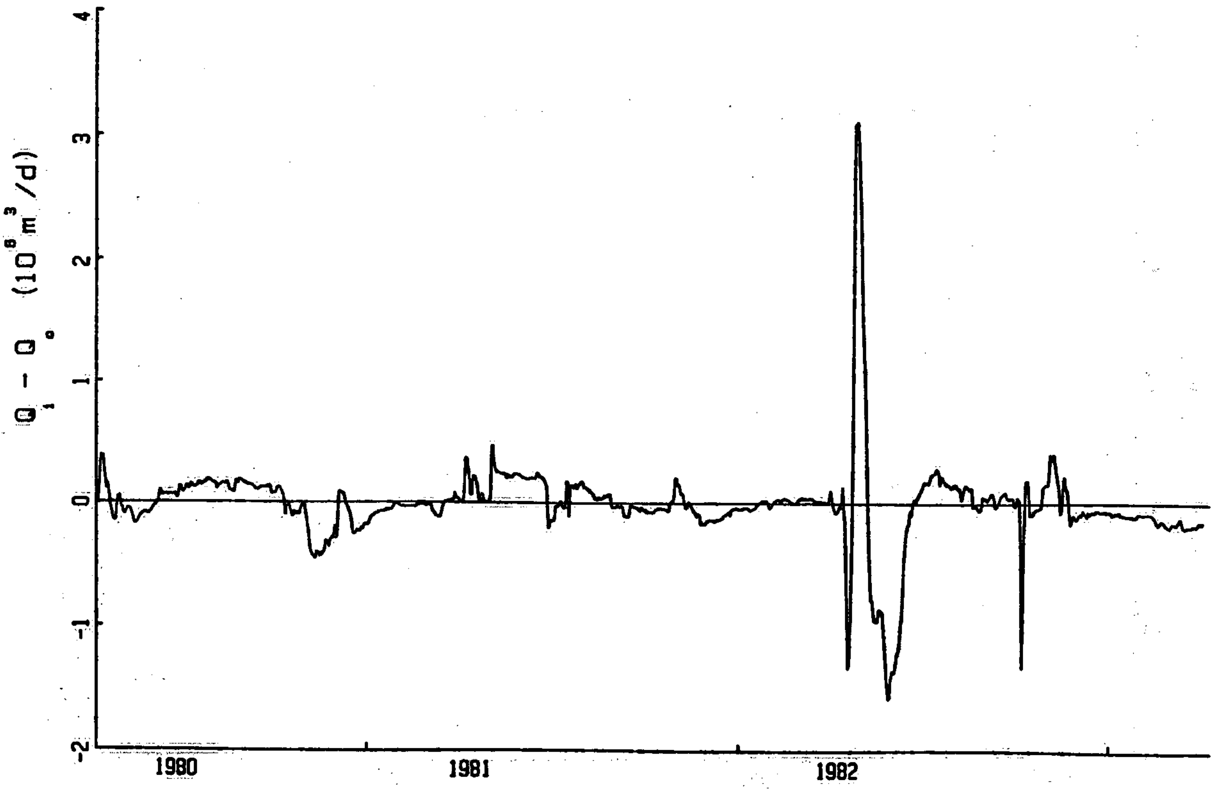

Figure 5. The difference between the inflow and the outflow from the Fishing Lakes from 1980 to 1983.

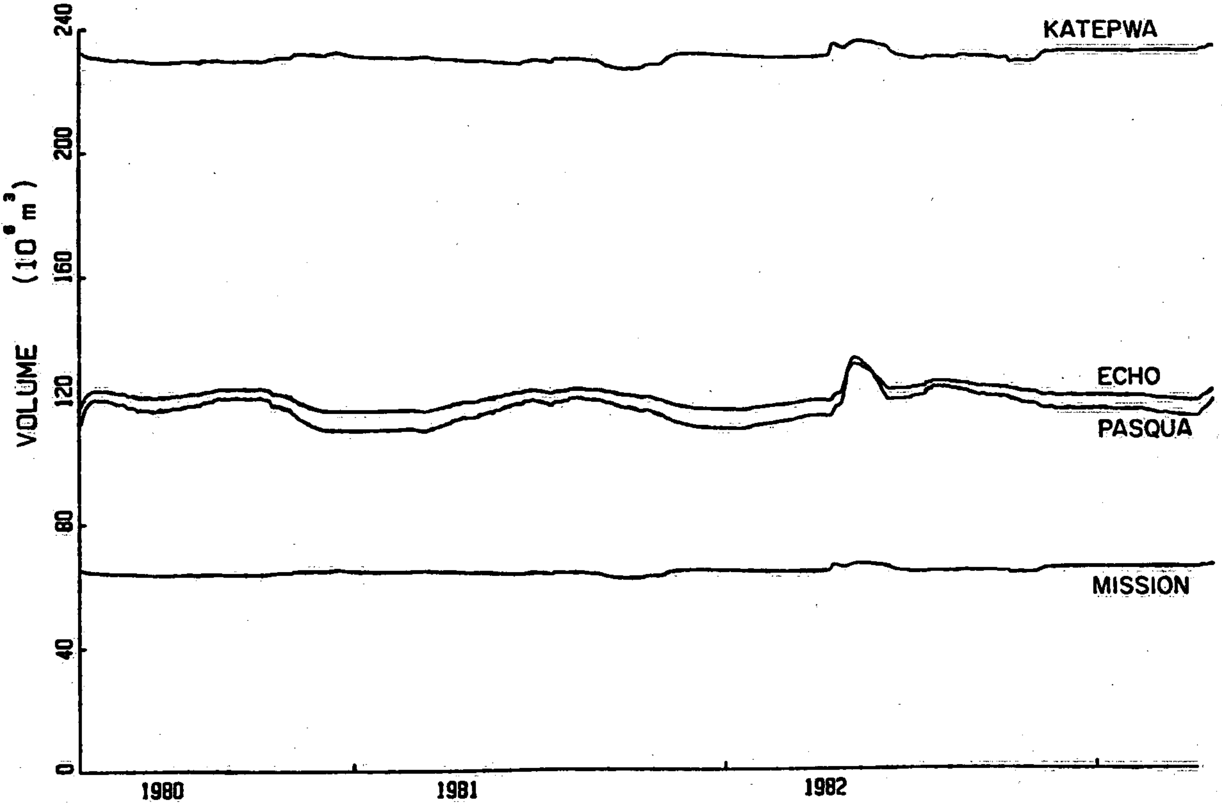

Figure 6. The variation in the lake volumes of the four Fishing Lakes from 1980 to 1983.

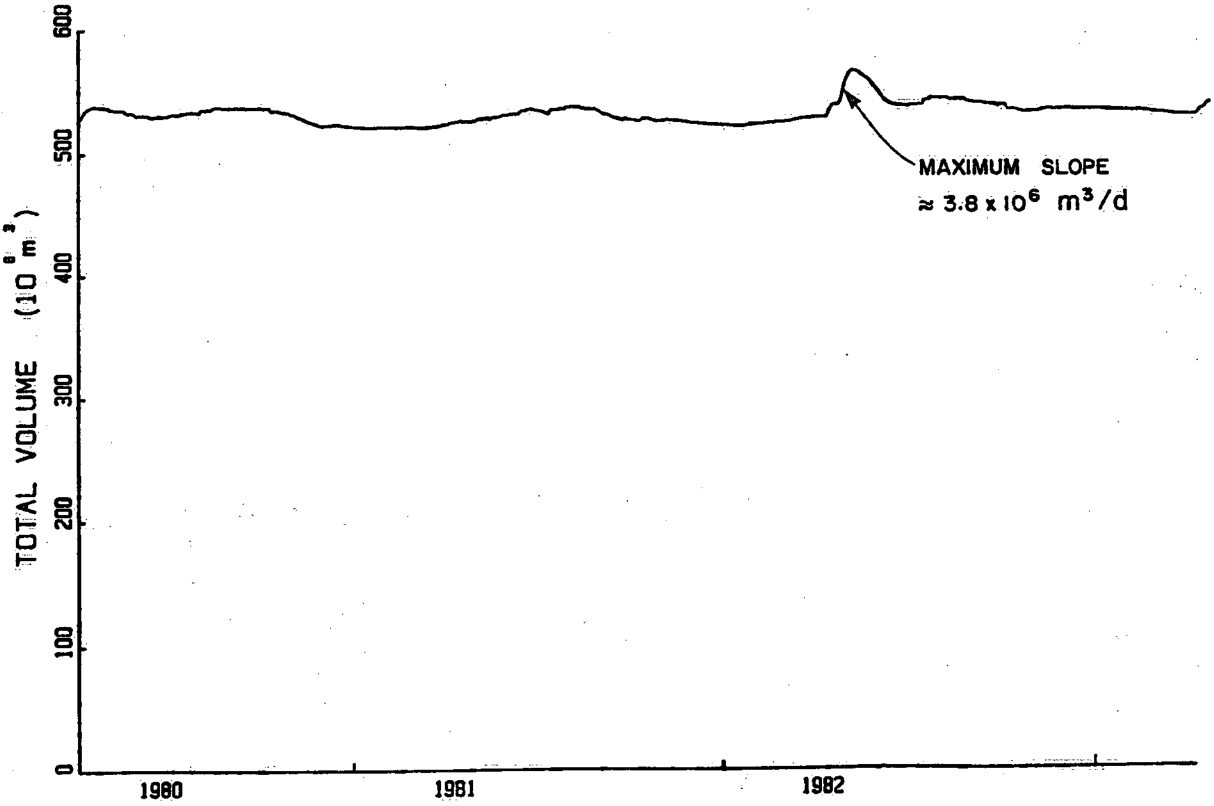

Figure 7. The variation in the total volume of the Fishing Lakes from 1980 to 1983.

that maximum ground-water inflow to the lakes would occur from April to August with the peak corresponding to the snowmelt. The water table decreased slightly during the rest of the year, presumably because of continued ground-water inflow to the lakes over the winter with no recharge of the water table through the frozen ground. From an examination of the water chemistry of Mission Lake and the local ground water, Christiansen et al. (1977) concluded that most of the water in Mission Lake originated as ground water. On the other hand, the water budget estimates made in this paper suggest that ground-water inflow is unlikely to be the dominant term in the water budget, although it may be significant in low flow years.

The Qu'Appelle River is the only surface outflow from the lakes. It is gauged at the outlet of Katepwa Lake. In addition to an unknown quantity of ground-water outflow, the only other water loss from the lakes is evaporation, which is not monitored on the Fishing Lakes. Cross (1978) used evaporation pan data with a 7-year mean of 650 mm/a in her water budget. Although evaporation pan data are still routinely collected by the Atmospheric Environment Service (AES), the relevance of such data to lake evaporation is suspect because of fundamental differences between energy and momentum balances in the pan and in the lake.

The temperature of Lake Diefenbaker (Fig. 1) is routinely monitored by AES and evaporation calculated using a mass transfer equation. A 10-year average annual evaporation is 760 mm/a for Lake Diefenbaker using this approach. Both estimates are about the same order as the annual evaporation estimated for the Great Lakes. In view of the high winds and low ambient humidity on the prairies during the open water season, one might expect that the annual evaporation from the Fishing Lakes would be much higher than the Great Lakes. On the other hand, prairie lakes have no evaporation losses for about 5 months each year because they are totally frozen over.

Since evaporation is difficult to determine accurately, no attempt was made to calculate it on a daily basis. Instead, an unknown flow term was calculated using

$$UQ = dV - Q_i + Q_o$$

This term contains the unmeasured direct runoff, the difference between precipitation to and evaporation from the lake surface, net ground-water input, and all errors accumulated in measuring the inflow, the outflow, and the change in lake volume.

Because UQ was calculated as the difference among three terms in the balance equation, it was expected that UQ would be noisy (i.e., that UQ would have large random fluctuations). It was also expected from the previous annual water budgets and the above considerations that UQ would be a small fraction of the inflow or outflow, but it is not. Figure 8 shows that not only is UQ very noisy, but also that many spikes are much larger than the maximum inflow, outflow, or even the net flow from the Qu'Appelle River. There are two obvious trends in UQ, however. First, the noise is much lower during the winter for each of the 3 years shown in Figure 8. Second, UQ integrates to a net inflow during the winter months and to a net outflow during the summer.

Much of the noise in UQ is simply due to measurement inaccuracy and accumulated error. For example, the large negative spike in UQ in April 1982 suggests that the accuracy of discharge computations decreases during the period of the spring flood.

There are two other likely sources of much of the noise in UQ. One is wind-induced oscillations or set-up of the lake surface that produces spurious changes in the computed lake volume. The second is a phase shift resulting from the use of daily averages that are centred on 12 noon for both the lake level and discharge data. In order to reduce the noise in UQ, the lake level data were smoothed with a 4-day digital filter. This filter eliminated most of the wind set-up fluctuations while simultaneously introducing a 12-hour phase shift required to compensate for the averaging method used for the daily data. UQ calculated from the filtered lake level data are shown in Figure 9. Most of the large spikes in UQ in Figure 8 have been eliminated, but the basic differences between winter and the open water period are still obvious. Although UQ in Figure 9 is now of the same order of magnitude as the inflow, outflow, or net flow, it is still very large when one considers that the local drainage basin is only about 10% of the area drained upstream from the lakes.

The net water gain during the winter is likely ground-water inflow. Local precipitation and evaporation, which tend to offset one another in annual water budgets, may account for the higher noise in UQ during the open water period since, on a daily basis, precipitation is usually low when evaporation is high and vice versa. The net water loss during the open water period is likely due to high evaporation on the prairies. This net water loss could conceivably result from ground-water outflow during the open water period, although the water table fluctuations presented by Christiansen et al. (1977) would suggest that ground-water flow is always into the lakes and is largest during the spring and summer. An inflow of ground water would require an even larger evaporation term to balance the water budget during the open water period.

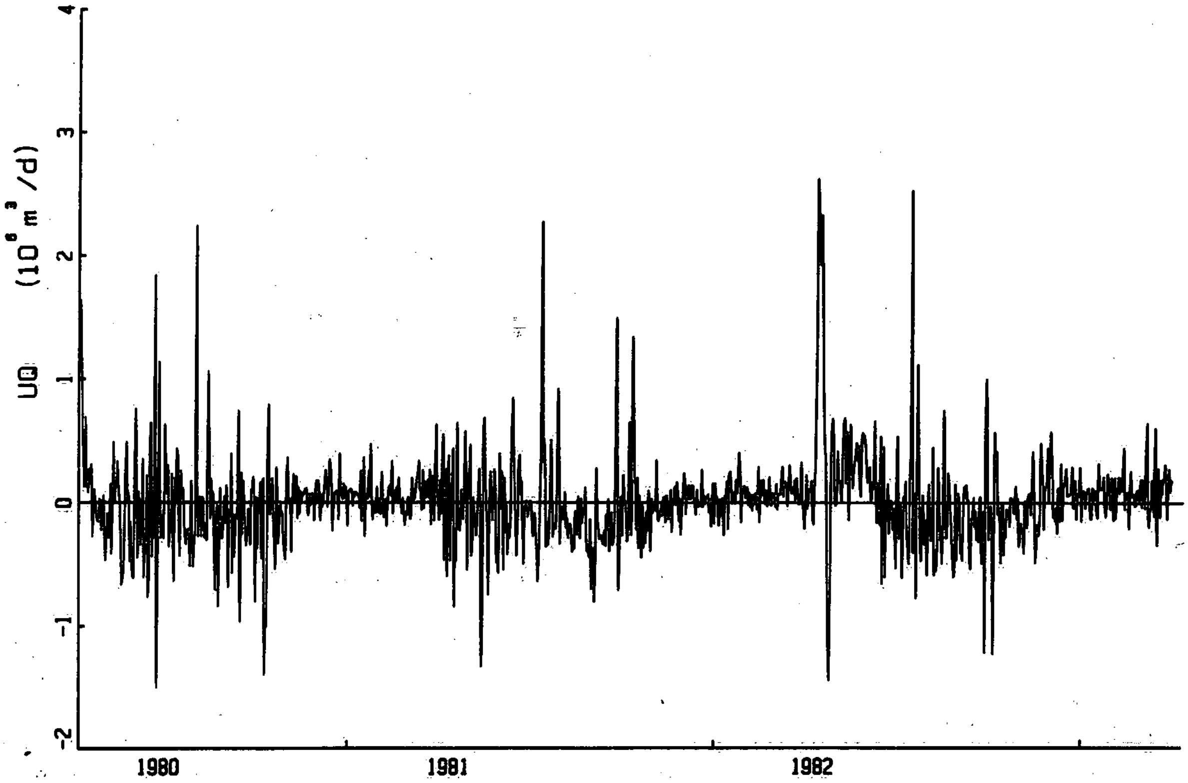

Figure 8. Variation in the unknown flow (UQ) from 1980 to 1983.

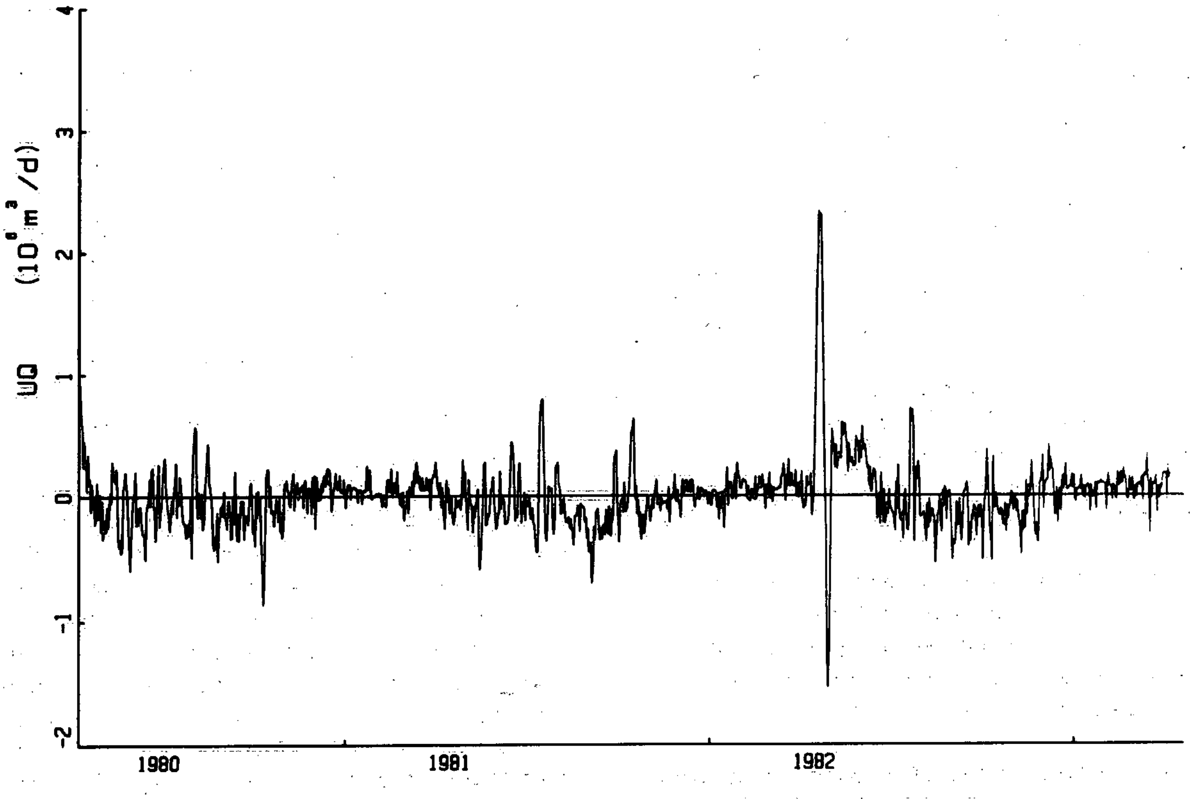

Figure 9. Variation in the unknown flow (UQ) after smoothing with a 4-day digital filter.

In winter, much of the noise in UQ results from random measurement error that contributes little to integral values. If it is assumed that there are no systematic errors in the discharge measurements, then some rough quantitative estimates can be made. Integrating the net inflow in Figure 9 over each 5-month winter period results in a suspected ground-water inflow of the order of 0.07×10^6 m^3/d. This net winter inflow did not vary much from winter to winter. Thus winter ground water may contribute significantly to the total winter inflow to the Fishing Lakes, particularly in low flow years. It is not possible to estimate net ground water during the open water period or to estimate the actual evaporation with any confidence using these data. From arguments presented by Christiansen et al. (1977), it is likely that ground-water inflow increases during the open water period. Even at a flow rate that is 2 to 3 times larger, the overall impact of ground water on the water budget appears slight except during low flow years.

MEASUREMENTS OF TOTAL PHOSPHORUS IN THE FISHING LAKES

All available phosphorus concentration measurements that were made immediately upstream from Pasqua Lake from 1970 to 1983 are shown in Figure 10. The inflow TP data collected prior to 1980 were previously examined in detail and edited by Cross (1978). The paucity of data prior to 1980 is obvious from Figure 10. Seldom were more than eight TP measurements made per year before the start of the WQB intensive sampling program in 1980. Although the first 10 years of record lacks detail, the entire data set is characterized by similarly high peak values and a high degree of variability. The numerous peaks in Figure 10 are extremely high values of TP concentration for any natural water system. Even the lowest inflow concentrations measured during this 13-year period were high compared with the concentrations (10-20 mg/m^3) required to produce algal blooms (Sawyer, 1947). Sawyer's criterion is the concentration level used by Vollenweider (1975) and others as the threshold value for eutrophic lakes.

The measured TP concentrations at the outflow of Katepwa Lake were much less variable than the inflow. The reduction in the level of fluctuations or noise in the phosphorus concentrations at the outflow is an expected result of phosphorus dynamics theory and demonstrates that lakes behave physically (as well as theoretically) like low pass filters. That is, fluctuations in inflow TP that occur at high frequency relative to the natural frequency of a lake ($1/\tau_p$) are heavily damped by the lake, while low frequency fluctuations pass through the lake unchanged. In effect, large spikes in inflow TP occur too rapidly for a lake to respond and are not detectable at the outflow. Some damping is readily apparent in Figure 11, which shows both the inflow and outflow TP concentration from the Fishing Lakes from 1980 to 1983. The fact that the measured outflow TP in Figure 11 contains some high-frequency noise may result from other causes, such as measurement inaccuracy, sampling variance, incomplete mixing in the lakes, or other local effects at the outflow that tend to make the outflow concentrations less representative of the actual lake concentrations. Sampling variance alone could account for most of the observed noise in the outflow TP shown in Figure 11. Stainton et al. (1974) have shown that phosphorus analysis of numerous samples taken from a homogeneous source containing particulates may have a relative standard deviation of ±20% or more.

SIMULATION OF OUTFLOW PHOSPHORUS CONCENTRATION FROM THE FISHING LAKES

Single-lake Model

Since there were no measurements made of the water flow between the various lakes, a single-lake model (equation [8]) of the Fishing Lakes was first used to simulate the outflow TP. Because of the seasonal variation in lake levels, the three-time-scale model was applied to a single lake with a volume equal to the total volume of the four Fishing Lakes at each time step (1 day).

Daily means of total lake volume and the inflow and outflow discharge were combined to determine two of the time scales to be input to the single-lake model equation. The resulting daily values of the inflow and outflow time scales from 1980 to 1983 are shown in Figure 12 and 13, respectively. There was no independent method of estimating the sedimentation time scale, so the one-point calibration procedure used for the Lake Washington simulation was adopted for the Fishing Lakes (Kenney, 1990b). The value calculated for σ using the first data point in the time series was so small that a constant value of zero was used in all the simulations.

The single-lake model was also run using the sparse total phosphorus data set available from 1970 to 1979 (Fig. 10). The model was driven by daily values of inflow TP that were calculated by linear interpolation from the few data points available. Daily values of the inflow and outflow time scales (Figs. 14 and 15) were calculated from daily estimates of the discharge to and from the Fishing Lakes and the total volume of the four lakes interpolated from monthly averages for that period.

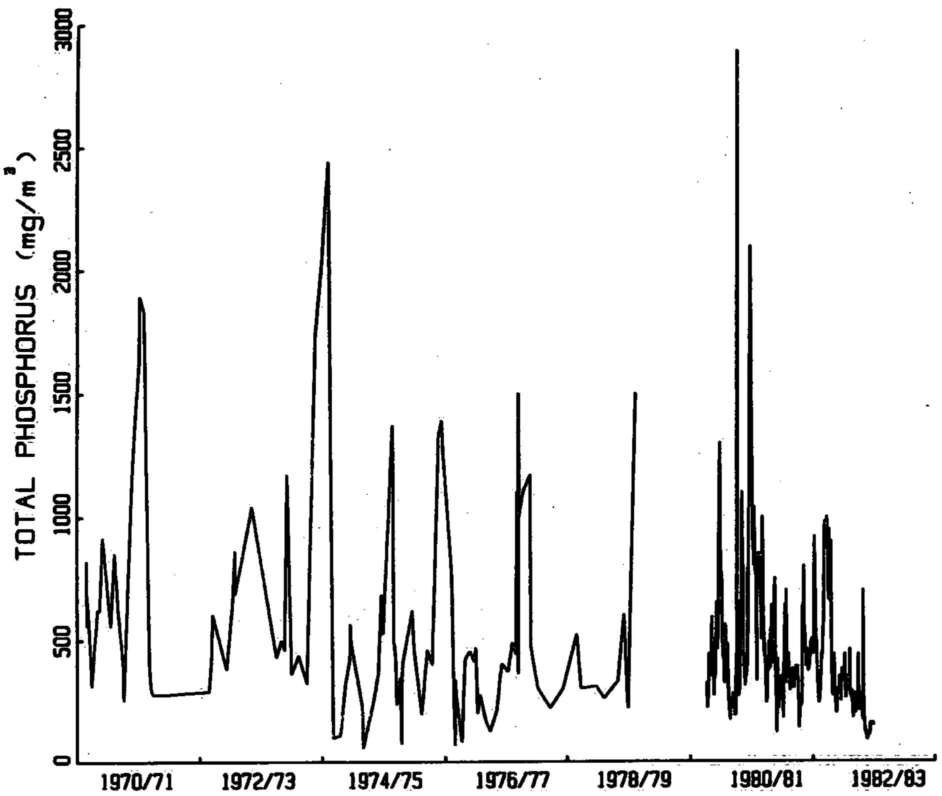

Figure 10. Concentration of total phosphorus in the inflow to the Fishing Lakes from 1970 to 1983.

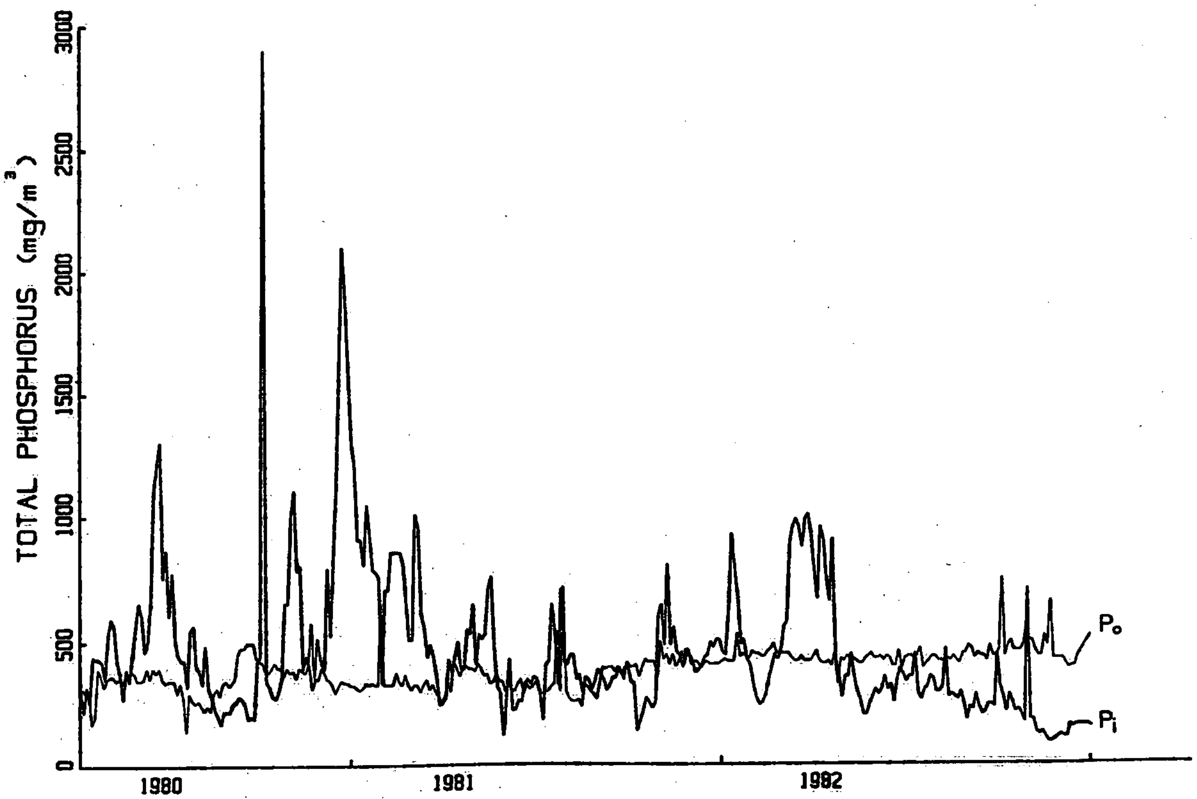

Figure 11. Concentrations of total phosphorus in the inflow and the outflow from the Fishing Lakes from 1980 to 1983.

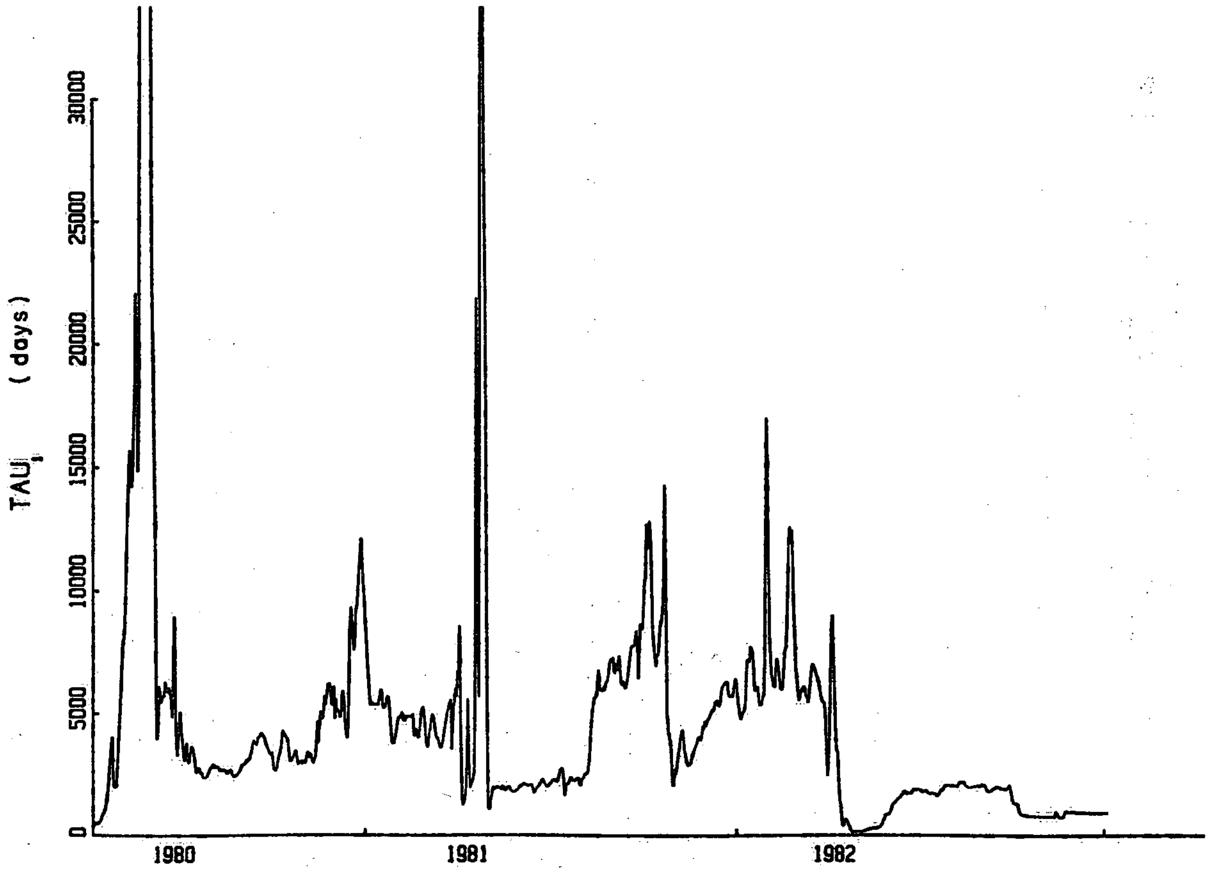

Figure 12. The inflow time scale to Pasqua Lake from 1980 to 1983.

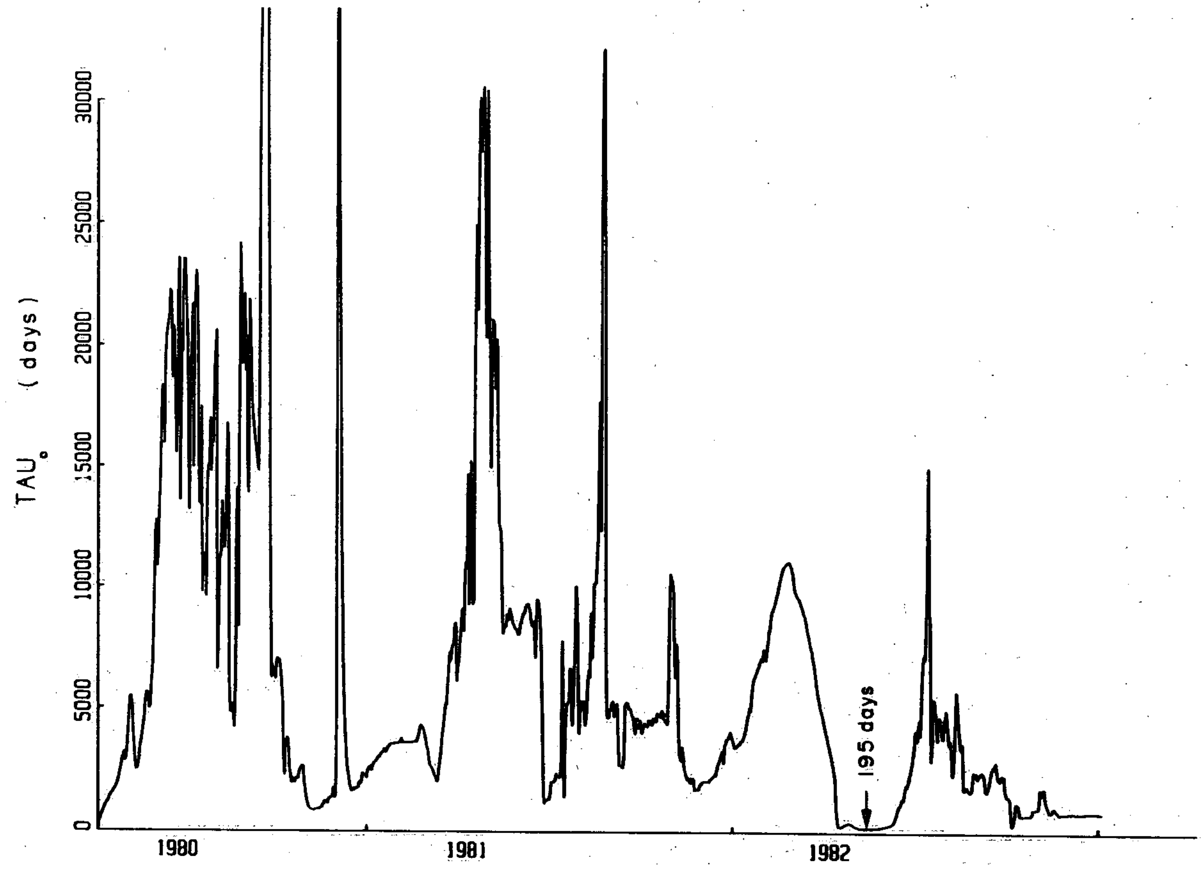

Figure 13. The outflow time scale from Katepwa Lake from 1980 to 1983.

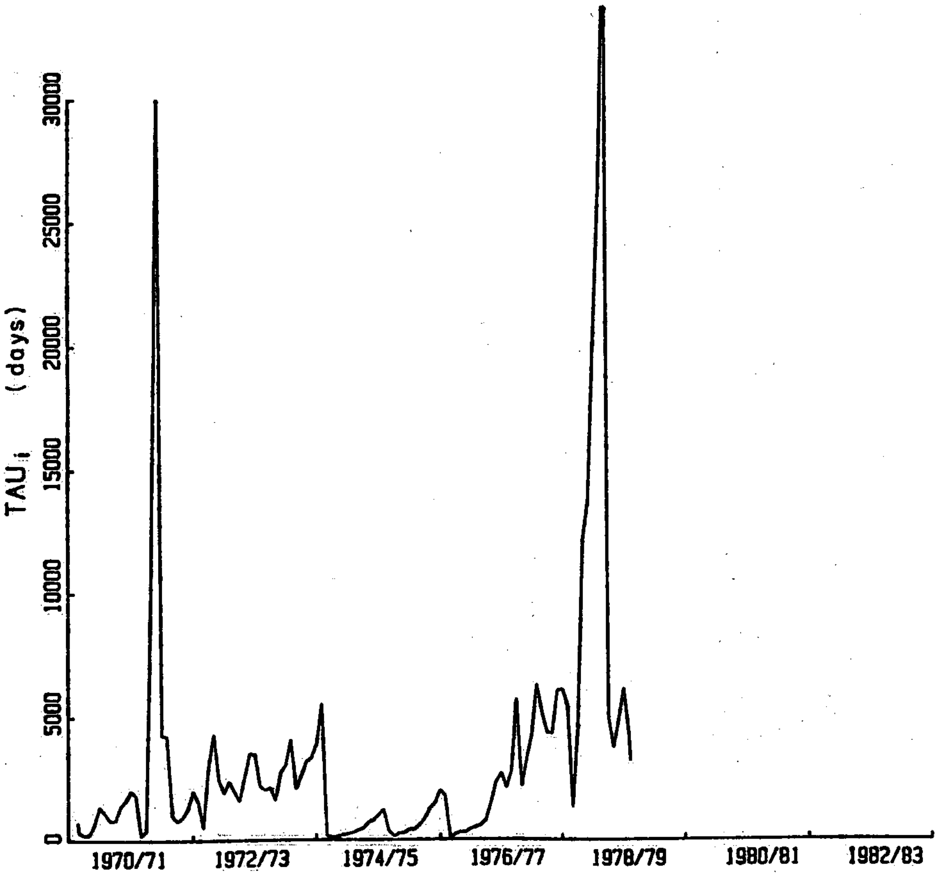

Figure 14. The inflow time scale to Pasqua Lake from 1970 to 1979.

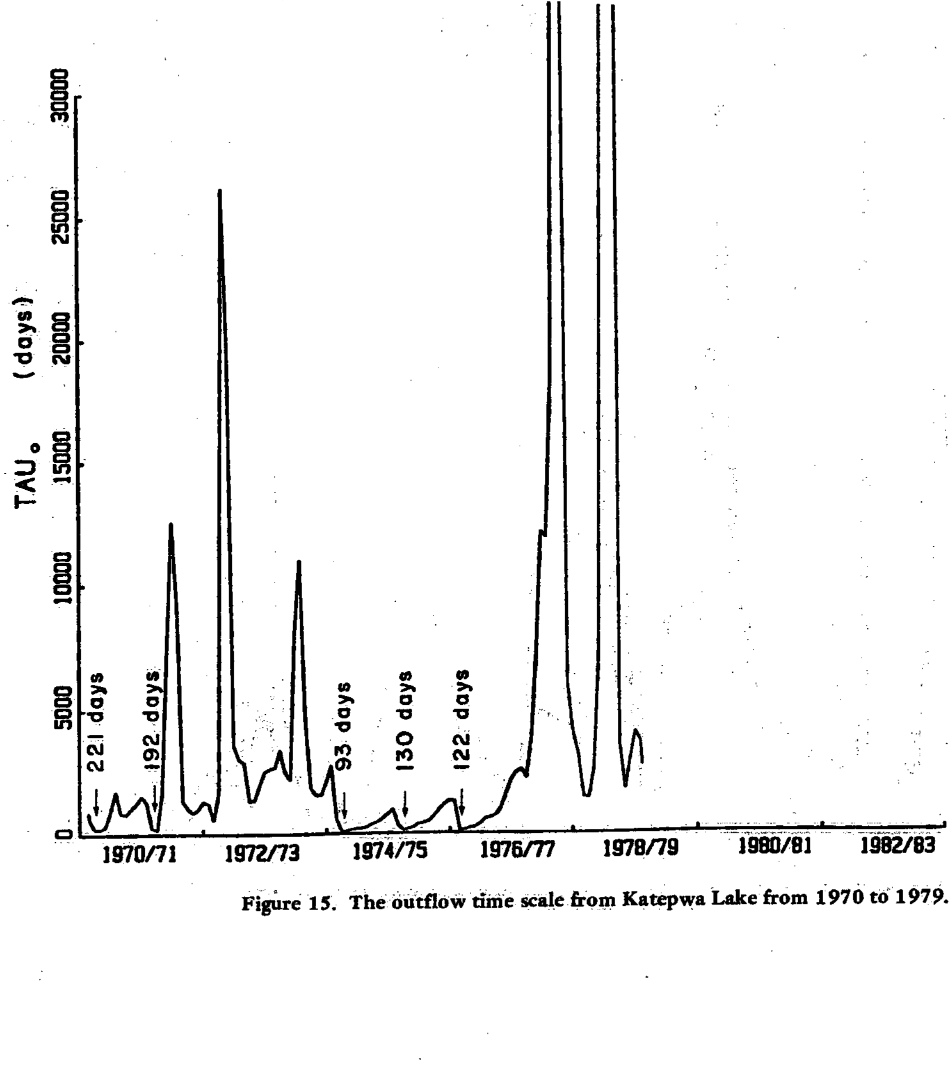

Figure 15. The outflow time scale from Katepwa Lake from 1970 to 1979.

The simulated outflow TP from 1970 to 1983 is shown in Figure 16 together with the measured phosphorus concentrations at the outflow of Katepwa Lake. Although the measured outflow TP concentrations are much noisier than the calculated TP, the overall simulation is relatively good. In particular, the major trend in the measured data (i.e., a reduction in TP from a level of about 500 to about 350 μg/L at the time of the 1974 spring flood) is reproduced by the simulation.

Lake Chain Model

The lack of discharge measurements between the individual lakes prevented direct application of the lake chain model (equations [2] to [5]) to the Fishing Lakes. Attempts to calculate the outflow from each of the four lakes using the water budget were unsuccessful. The calculated outflows were often negative, which corresponds to the unstable case of a negative time scale in the model. The reason for the lack of success in calculating outflows from each lake was the large unknown flow term in the water budget.

In order to assess the lake chain model in the Fishing Lakes, a more simplified approach to the water budget was then taken. The difference between the water inflow to Pasqua Lake and the outflow from Katepwa Lake was prorated among the four lakes. Water inflow and outflow times scales were then calculated for each of the four lakes using their individual volumes at each time step.

The lake chain model was also run to simulate both data sets. The results are shown in Figure 17. There are some minor differences between the lake chain model results and the single-lake simulation shown in Figure 16, but the major trends are identical. For example, both simulations clearly illustrate the importance of the 1974 flood on the water quality in subsequent years.

DISCUSSION

Regina Sewage Treatment Plant

One of the objectives of the WQB intensive sampling program was to evaluate the effects on the Fishing Lakes of additional treatment of Regina's sewage that began in 1976. The final results of the WQB program are presented in Munro (1986). A cursory examination of Figures 16 and 17, however, shows no reduction in the simulated TP outflow that could be directly associated with the introduction of tertiary treatment. A similar null response is seen in the measured inflow and outflow TP data.

Impact of the 1974 Flood

The most striking feature of the behaviour of TP in the Fishing Lakes is the influence of the 1974 flood. For 4 years prior to the 1974 spring flood, the TP at the outflow averaged nearly 500 μg/L. Following the flood, the outflow TP remained at about 350 μg/L. This decrease is seen in the measured outflow TP data as well as in the simulation. A similar decrease occurred in the measured inflow TP. It is not immediately obvious, however, why the 1974 spring flood resulted in such a significant drop in TP.

One complication to be considered is the possibility that the 1974 decrease resulted from a change in the methodology used to measure total phosphorus concentrations. The WQB changed its method of measuring TP in 1974, but not all sampling sites were changed simultaneously. There has been no reported decrease in the concentration of total phosphorus measured at other WQB sites, however, as a result of the change in the WQB analytical techniques. Furthermore, much of the TP data used in this study was supplied by the Province of Saskatchewan, and there was no change in its analytical procedure for determining TP concentrations during that time.

The most probable conclusion is that the decrease in TP that accompanied the 1974 flood was a real decrease and not simply a result of the change in analytical technique introduced at that time by WQB. Although the 1974 spring flood was the largest flood during the 13 years of record, it is not known why it had such an impact on TP concentrations entering the Fishing Lakes. On the other hand, the reduction in the outflow concentration is readily explained in terms of the phosphorus dynamics. The reduction in inflow TP occurred at a time when the lakes were capable of an immediate response, that is, when τ_o was small.

Simulation Accuracy

Input data required for the present simulation were a time series of input TP concentrations to force or drive the model and corresponding time series of the time scales that characterize the phosphorus dynamics of the lakes. In general, the length of the input time series required is several times longer than the time scale that characterizes the dynamics. The accuracy of the simulated outflow TP can be no greater than the accuracy of the data input to the model. The simulation of TP in the Fishing Lakes was hampered not so much by the inaccuracy of the input data as by the lack of input data. There were large gaps in the data set from 1970 to 1979 that required lengthy interpolations. For example, a single data point derived from one instantaneous sample was used to represent the TP input to

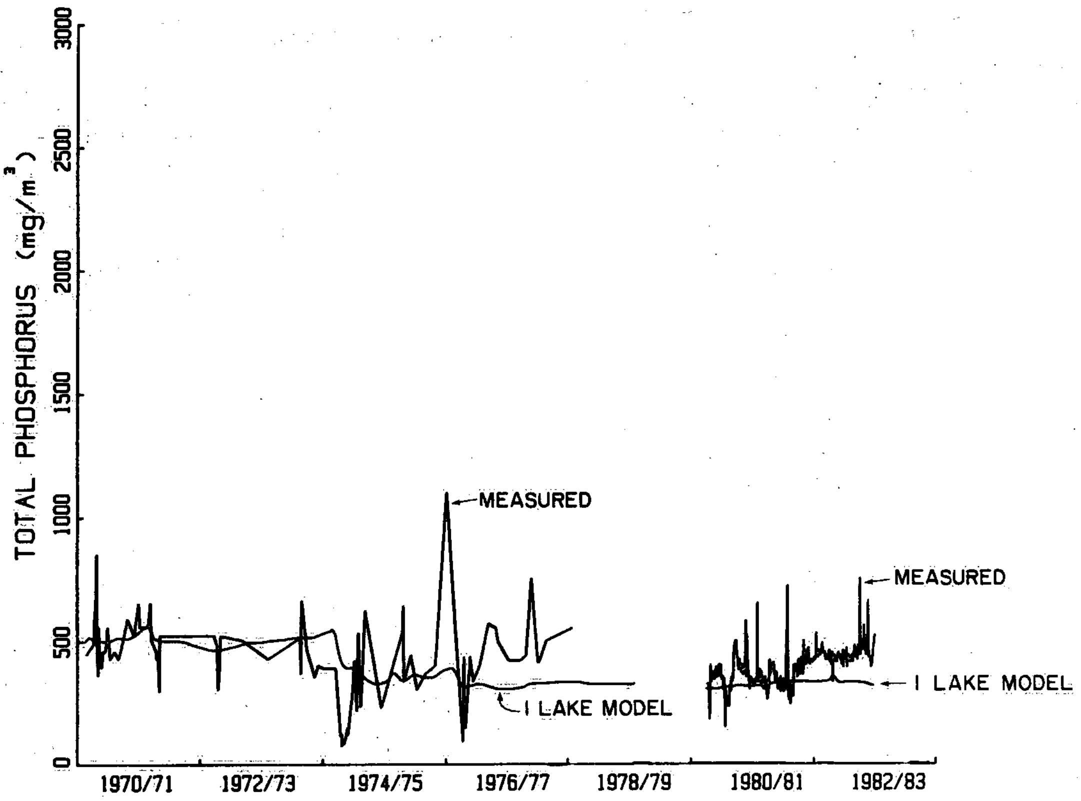

Figure 16. The total phosphorus concentration in the outflow from Katepwa Lake compared with the simulated TP concentration computed with the single-lake model.

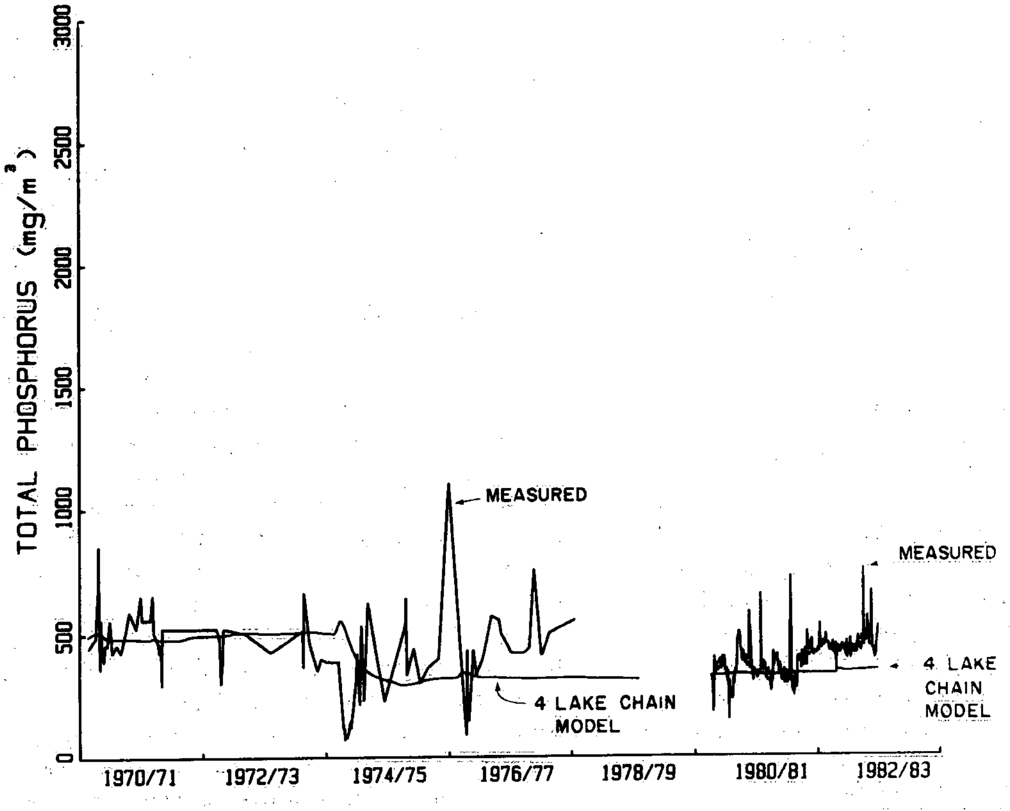

Figure 17. The total phosphorus concentration in the outflow from Katepwa Lake compared with the simulated TP concentration computed with the four-lake model.

the Fishing Lakes for over one year in 1971/72. Given the sparse input TP data set, the simulations are considered to be excellent. The measured output TP is much noisier than the simulated output TP, but the noise may be attributed mainly to sampling variance. Incomplete mixing in the lakes may also have contributed to the noise in the output TP.

It is difficult to assess which simulation is more representative of the outflow TP from the Fishing Lakes. In theory, the single-lake simulation is less accurate since it ignores the obvious physical differences between a large single lake and a chain of smaller lakes. On the other hand, actual measured inflows and outflows were used for the single-lake model, while the lake chain model used calculated values for the between-lake flows. Although it was shown theoretically that the four-lake chain model responds more quickly to changes in input TP than the single-lake model, the two simulations show only minor differences. This is largely because phosphorus dynamics in the Fishing Lakes were dominated by the phosphorus outflow time scale, which was highly variable. Other lake chains with a more constant discharge would demonstrate the inherent difference in response time of the two models more clearly. Since both models simulate the major features of the measured outflow reasonably well, an exhaustive comparison of the two results is not warranted. Phosphorus contained in the ground water and other unknown inflows likely limits the maximum accuracy of both simulations in the Fishing Lakes.

Sedimentation of Phosphorus

The absence of any detailed measurements on sedimentation rates in the Fishing Lakes precludes direct estimation of the sedimentation constant. Furthermore, it is unlikely that any of the devices conceived to date to measure in situ sedimentation rates produce unbiased results. Any such physical device must necessarily disturb the natural horizontal lake currents and the turbulent fluctuations that suspend the particles. Also, the inherent nonstationarity of the sedimentation process results in periodic negative fluxes within the water column (Kenney, 1985). The biological conversion of dissolved TP to particulate TP may also be an important factor controlling the sedimentation time scale. While the present phosphorus dynamics models allow for a time-varying sedimentation constant, there is no independent method available to determine it.

Several indirect methods to determine σ were proposed in Kenney (1990a). Each method depended upon the applicability of the two-time-scale model. Any sources or sinks not explicitly taken into account were simply absorbed in the sedimentation constant. The simplest method is, in effect, a one-point calibration of the model equations using the first data point in the time series. Using this approach on Lake Washington resulted in a sedimentation time scale of 706 days. A similar approach was adopted for the Fishing Lakes analysis using the first point in the 1980/83 record. The resulting value of σ was so small that $\sigma = 0$ was used in all subsequent analyses. With $\sigma = 0$, the phosphorus dynamics model reduces to a two-time-scale model: the inflow and outflow time scales. The dynamic response of the lakes is determined solely by the latter. A value of $\sigma = 0$ also means that there is no net sedimentation in the Fishing Lakes. In effect, the Fishing Lakes are saturated with total phosphorus.

Physical sedimentation of particulate phosphorus does occur, however. When compared with the flow, available data show a drop in particulate TP and an increase in dissolved TP in the outflow from the Fishing Lakes. A similar change in phosphorus form occurred in Lake Washington. This change in the form of phosphorus is not included in the present models, which are only capable of describing net sedimentation as a sink. A simple extension of the present model has been derived to account for the sediments as a source of TP, but there are no sediment phosphorus data with which to evaluate the model at this time.

SUMMARY AND CONCLUSIONS

The application of lake phosphorus dynamics has been extended to describe phosphorus concentrations in the outflow from a chain of large prairie lakes. The dynamic or frequency response of the lakes was shown to be determined by the outflow time scale. Generally, the time scale was so large (greater than the 13-year period of available record) that the Fishing Lakes did not respond to sharp peaks in input TP regardless of their size. Only during the spring floods of 1974, 1975, 1976, and 1982 was the outflow time scale sufficiently small to allow a significant response in the outflow TP within the period of available data. Of the four flood years, the 1974 flood was the largest. Not only was the time scale greatly reduced, but the 1974 flood was also accompanied by a reduction in the inflow TP. The combination of low inflow phosphorus concentrations and high flows resulted in the large reduction observed in the outflow phosphorus concentrations.

The Fishing Lakes were shown to be saturated with phosphorus. There was no net sedimentation of phosphorus in the lakes, although there was a reduction of particulate

TP and an increase in dissolved TP in the outflow. The Lake Washington data showed a similar change in the form of phosphorus from inflow to outflow, but had a sedimentation time scale of about 2 years.

The large spring flood in 1974 had a greater effect on reducing P_L in the Fishing Lakes than the Regina tertiary treatment plant that commenced operation in June 1976. The simulated lake phosphorus dropped over 100 mg/m^3 to about 350 mg/m^3 during the flood and has remained at about that level since 1974. The measured P_L was much noisier, but it also showed that a marked decrease accompanied the 1974 flood. On the other hand, there has been no detectable response in the Fishing Lakes to the tertiary treatment of Regina sewage, either in the measured or in the simulated outflow TP. Nor has there been any detectable response in the inflow TP, although the lack of measurements in 1978 and 1979 detracts somewhat from the confidence with which one can make such statements.

The phosphorus concentrations in local runoff to the lakes, as well as that upstream from Regina and Moose Jaw, are an order of magnitude greater than Sawyer (1947) found for the production of algae blooms. Hence the lakes are supplied with TP-enriched water from all inflows except direct precipitation and are likely to produce immense algal blooms even without municipal effluents. It is not known how much agricultural practices contribute to the high TP concentrations in the local runoff or how much TP is supplied by the natural prairie soils.

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