

Application of a Linked Watershed Waterbody Model to Kingston Harbour in Jamaica

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Abstract Components of the Linked Watershed Waterbody Model (LWWM) developed by Dames & Moore for the Southwest Florida Water Management District has been applied to Kingston Harbour, Jamaica. The model is a linkage between ARCInfo GIS, the Storm Water Management Model (SWMM) and Water Analysis Simulation Program (WASP) supported by the United States Environmental Protection Agency. The model is a tool for managing non-point and point source pollution by providing a framework in which pollution sources can be removed and the impact on the harbour assessed. The GIS component of the model utilized input data on land use, soils and areas to generate an input file for SWMM. Streamflow and water quality constituents were simulated by SWMM for the 300 square mile watershed. Flows and pollutants were routed to the harbour for input to the WASP model in which the hydrodynamics, ammonia, nitrate+nitrite, organic nitrogen, orthophosphate, organic phosphorus, dissolved oxygen, biochemical oxygen demand (BOD) and chlorophyll-a in the harbour were simulated. There was a paucity of concurrent data for model calibration but the simulation demonstrated that the model can be successfully used as a management tool for developing pollution reduction goals for the harbour.

Aplicación de un Modelo Eslabonado de Cuenca Hidráulica en el Puerto de Kingston, Jamaica

Resumen Los componentes del Modelo Eslabonado de Cuenca Hidráulica (Linked Watershed Waterbody Model, LWWM) elaborado por Dames & Moore para la Agencia de Gestión de Agua del Suroeste de la Florida (Southwest Florida Water Management District) ha sido aplicado al Puerto de Kingston, Jamaica. El modelo esta unido entre ARCInfo GIS (Sistema de Información Geográfico) y los modelos SWMM (Storm Water Management Model) y WASP (Water Analysis Simulation Program) que son respaldados por la Agencia de la Protección Ambiental de los Estados Unidos (USEPA). El modelo es un instrumento para la gestión de los orígenes de contaminación puntuales y no puntuales proveyendo un marco por medio del cual los orígenes de contaminación se puedan eliminar y el impacto en el puerto evaluado. El componente GIS del modelo utilizo datos de uso de tierra, suelos, y áreas para generar un archivo de entrada para SWMM. La corriente y los constituyentes de calidad de agua fueron simuladas por SWMM para la cuenca de 300 millas cuadradas. Flujos y contaminantes fueron enviados al puerto como datos de entrada al modelo WASP en el cual se simulo la hidrodinámica, amonio, nitrato+nitrito, nitrógeno ortofosfato orgánico, fosfato orgánico, oxígeno disuelto, demanda bioquímico de oxígeno, y clorofila-a en el puerto. Hubo una insuficiencia de data concurrente para la calibración del modelo pero la simulación demostró que el modelo puede ser usado exitosamente como instrumento de manejo para el desarrollo de metas de reducción de contaminación en el puerto.

INTRODUCTION

Dames & Moore has developed a linkage between a Geographic Information System (GIS), the United States Environmental Protection Agency (USEPA) Storm Water Management Model (SWMM), and Water Analysis Simulation Program (WASP). The linkage termed the LWWM (Linked Watershed Waterbody Model) was used to simulate the watershed of Kingston Harbour and the processes within the harbour. Watershed modelling included simulation of flows and water quality constituents: total nitrogen, total phosphorus, and biochemical oxygen demand (BOD). Waterbody modelling included simulation of the harbour's hydrodynamics and water quality constituents: ammonia nitrogen, nitrite+nitrate nitrogen, organic nitrogen, orthophosphate, organic phosphorus, BOD, dissolved oxygen, and chlorophyll-a.

At the time of writing this paper, the model was set up with available data and, although used for the simulation described above, was not completely calibrated. Streamflow was calibrated for some upper sections of the watershed where one year (1994) of hourly rainfall and daily streamflow data were available. However, streamflow data were not available for the lower sections of the watershed, and water quality data were not available for the same period for the harbour and watershed. The modelling effort, however, does identify a proposed methodology, tools, and data requirements. This paper therefore presents the work accomplished to date, identifies data requirements for refining and further developing the model, and shows how the model can be used as a management tool for defining pollution load reduction goals (PLRGs).

DESCRIPTION OF WATERSHED AND HARBOUR

Kingston Harbour and its watershed are located in southeast Jamaica. Sentar (1992) describes the harbour as a large natural embayment approximately 10 miles long by 2 miles wide. A relatively shallow section, Hunts Bay, is connected to the harbour by a 200 m wide inlet. The drainage to the harbour consists of a 300 square mile catchment, much of which is within the Rio Cobre basin. The Rio Cobre's upper reaches flow over a highly impervious geologic formation to very pervious areas, and finally over an alluvium region where channel losses occur (White *et al.*, 1983; Walters, 1988). Wade (1976) conducted an extensive investigation of the water quality in the harbour and describes a significant degradation of the water quality when comparing the periods 1971-1971 and 1973-1975. Furthermore, the quality in Hunts Bay was worse than that within the harbour. Douglas & Gabbidon (1992) reported on stormwater quality data collected in the tributaries and showed BOD values ranging from 1.7 to 60 mg l⁻¹.

MODEL FRAMEWORK

The model framework consists of SWMM and WASP used within the platform of the LWWM. The model interactively links GIS ARC-INFO with the RUNOFF block of SWMM and WASP. The framework is such that each model component is used

separately to generate input files that can be utilized by other components in the following sequence: (a) GIS files with land use and soil data are model inputs which are used to create a Geographic Data File (GDF) file, which is used to create a part of the SWMM input file; (b) the LWWM prompts the user for other relevant information which is used to create the remainder of the SWMM input file; (c) SWMM is used to create files with water quality and quantity information that is read by WASP; and (d) WASP is used to simulate water-body pollution dynamics.

AVAILABLE DATA

In order to complete the modelling study, data are required to define generally fixed physical features of the watershed and harbour. In addition, hydrologic or meteorologic variables that define changes in input or output for water quantity or quality are required. The data that are required and the availability are described in the following subsections.

Physical dimensions of the harbour

Dimensions of the harbour and Hunts Bay were obtained from a 1:50 000 map (Surveys Department, 1984) and by verbal communication with Dr Dale Webber of the University of the West Indies. Spatial configuration was from the map, whereas an average depth of 14 m in the harbour and 2.5 m in Hunts Bay was from Webber (personal communication). Details available from other studies were not used in this initial setup but are recommended as a refinement of the model setup.

Rainfall

Data for four raingauges located in the upper Rio Cobre basin (Upper Kingston Harbour watershed) were available from the Jamaica Water Resources Authority. The locations of the gauges are shown in Fig. 1. The data consisted of hourly rainfall for 1994 and showed an annual rainfall variation from 139.7 to 116.8 cm with a maximum intensity of 9.4 cm h^{-1} . Data were not available for the lower basin. Based on historical data the rainfall in the lower basin is expected to be less than that in the upper basin. Consequently, a fifth rainfall record was incorporated in the model as 60% of the average in the upper basin. Recording of hourly rainfall for the lower basin is therefore a recommendation for refinement of the model.

Wind

Daily data on wind speed were available for the Norman Manley International Airport (NMIA) from the Jamaica National Meteorological Service (JNMS). The record was obtained from an anemometer 10 m high as required by WASP.

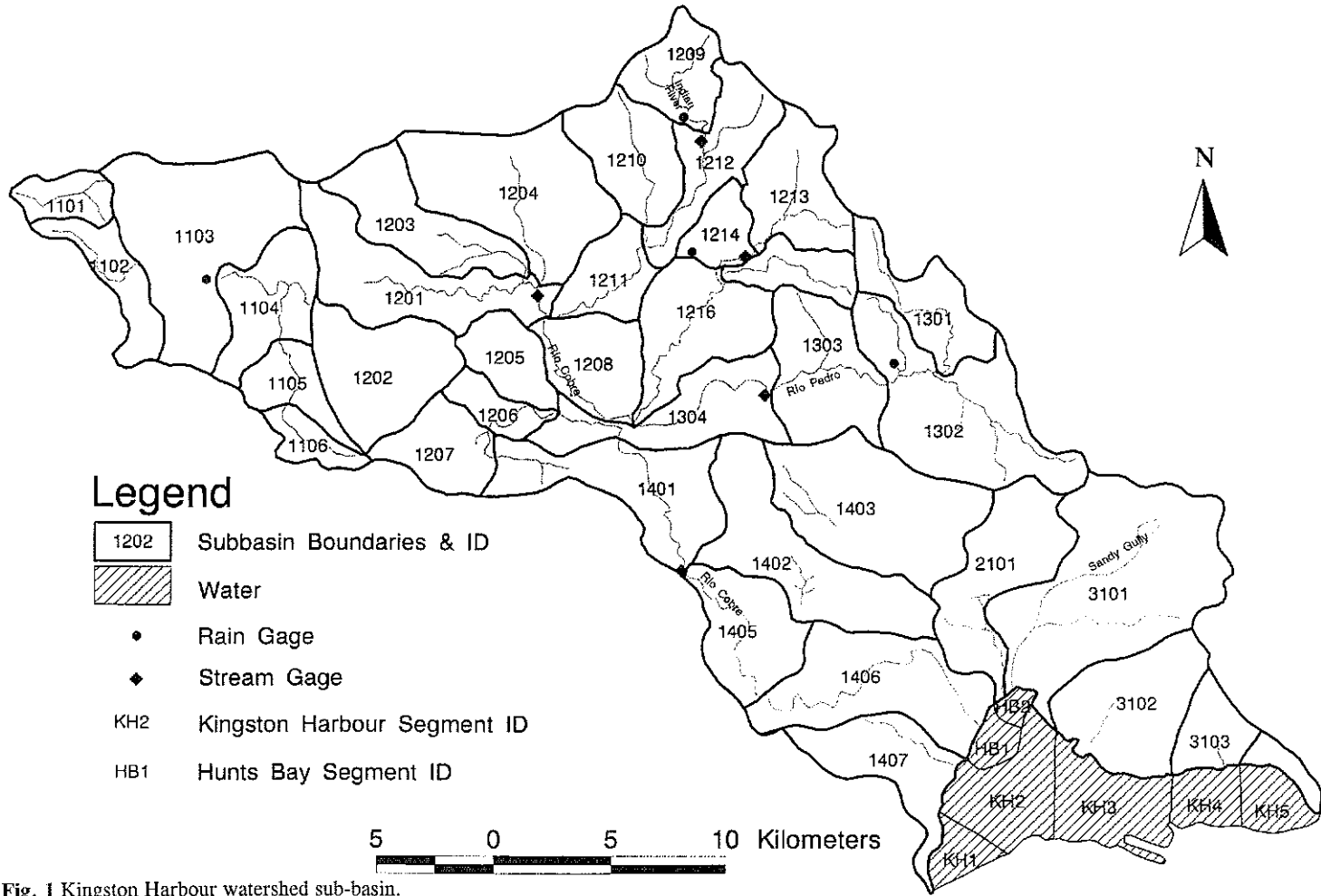


Fig. 1 Kingston Harbour watershed sub-basin.

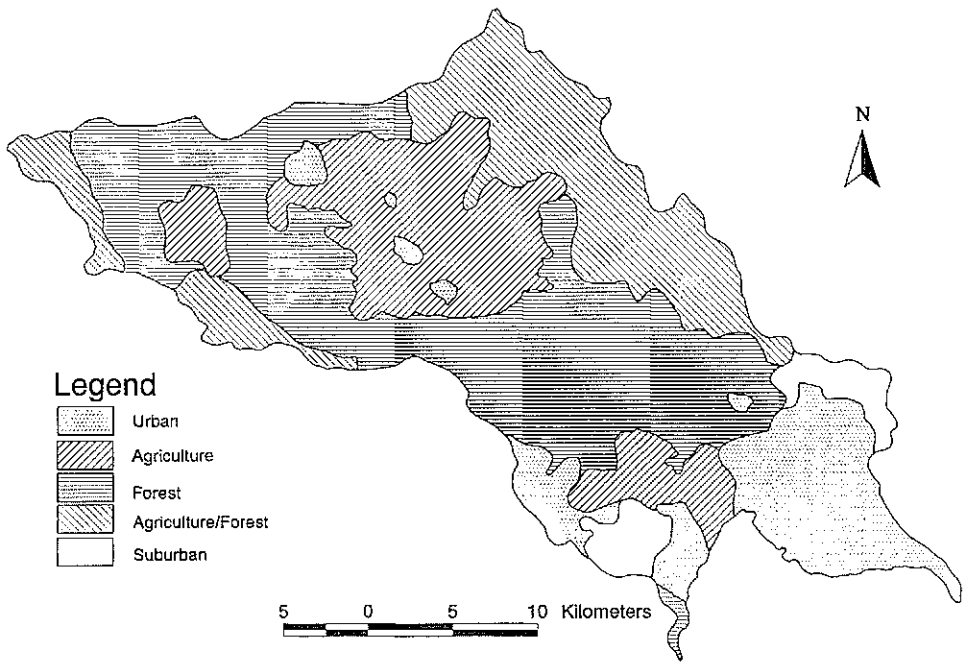


Fig. 2 Kingston Harbour watershed land use.

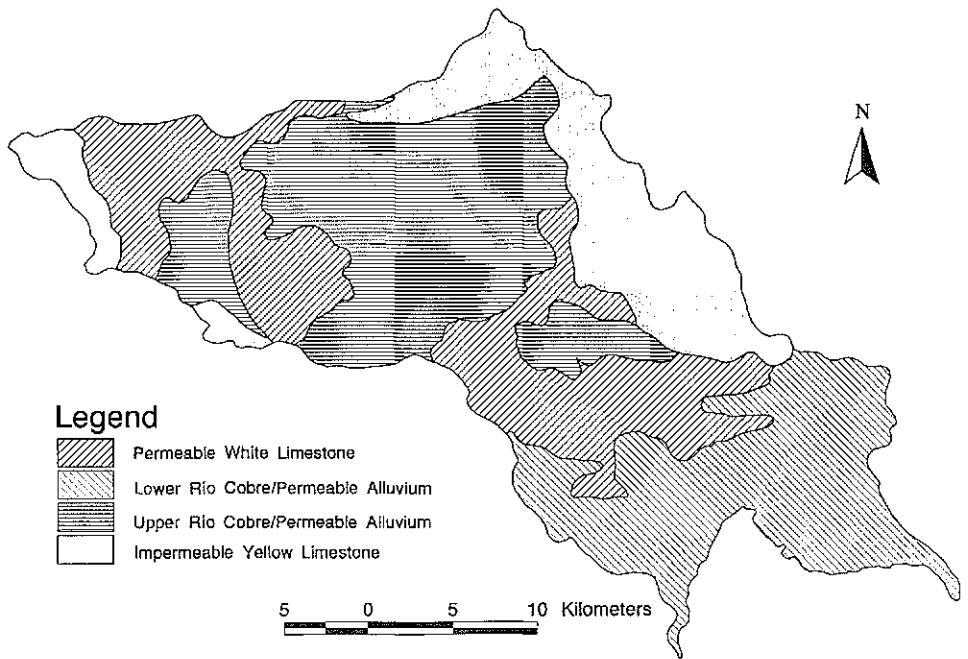


Fig. 3 Kingston Harbour watershed geology/soil classification.

Solar radiation

Data on solar radiation for 1994 were also available from JNMS for NMIA. The data showed that solar radiation varied from a minimum of 13.3 MJ m⁻² to 26.3 MJ m⁻² in August.

Evaporation, streamflow and harbour hydrodynamics

Evaporation estimates were based on techniques for estimating potential evaporation developed by Walters (1980). Daily streamflow data were available for five gauges whose locations are shown on Fig. 1. Hydrodynamic records of tidal movement and velocities within the harbour were not available. For modelling purposes, a latitude dependent tidal variation of two highs and two lows within a 25-h period with an amplitude of 0.67 m was assumed.

SWMM MODELLING

The basin was subdivided into 37 sub-basins shown in Fig. 1. Maps of land use, and soils/geology were prepared and digitized in the ARC-INFO format (Figs 2 and 3). Land-use categories shown in Fig. 2 are urban, agriculture, forest, agriculture/forest mixed and suburban. Typically, for some applications hydrologic soil groups are utilized. However, part of the watershed is within a karstic region where drainage is governed by rock formation rather than soils. For example, in a northwestern section of the watershed, there are areas with high infiltration rates based on the very permeable white limestone. Much of the infiltrated water, however, flows through fissures and caverns and reappears as streamflow downstream. Consequently, the typical infiltration rates for hydrologic soil groups were not utilized, but were determined by trial and error for the study area. The soil/geology groups utilized were:

- A Permeable White Limestone
- B Lower Rio Cobre and Liguanea Permeable Alluvium
- C Upper Rio Cobre Permeable Alluvium
- D Impermeable Yellow Limestone.

For SWMM modelling the Horton infiltration routines were utilized with the maximum infiltration rates of 0.03, 0.10, 2.54 and 0.08 cm h⁻¹ for Groups A, B, C and D, respectively. Minimum rates were 0.03, 0.08, 1.3 and 0.05 cm h⁻¹ for Groups A, B, C and D, respectively. The rates for Group A were selected to be low to account for the fact that the infiltrated water reappears as runoff at downstream gauging stations.

SWMM was also set up to simulate water quality constituent total nitrogen, total phosphorus and BOD. The algorithm for simulating water quality as a function of washoff from various land uses was utilized. Land use specific data were not available for the watershed and typical Event Mean Concentration (EMC) were utilized as shown in Table 1.

Flow and water quality were simulated in the RUNOFF block and routed through the TRANSPORT block with decay coefficients of 2.15, 0.05 and 0.10 day⁻¹

Table 1 Event mean concentration (mg l^{-1}) for water quality constituents.

| Constituent | Urban | Agriculture | Forest | Agri/forest | Suburban |
|-------------|-------|-------------|--------|-------------|----------|
| TN | 2.50 | 2.50 | 1.00 | 1.70 | 2.00 |
| TP | 0.50 | 0.30 | 0.05 | 0.20 | 0.30 |
| BOD | 11.50 | 4.00 | 1.50 | 2.50 | 5.00 |

TN: total nitrogen; TP: total phosphorus.

for TN, TP and BOD, respectively. Although water quality data were not available for the 1994 simulation period, data for 1992 were examined to ensure that reasonable values were simulated. The calibration curves for the most downstream streamflow station are shown as Fig. 4. Baseflow or point source loads were not simulated within SWMM but were added as a constant to the results for calibration purposes. The modelling effort emphasized stormwater runoff which contributes extremely high pulses of pollution to the harbour. Point source loads and baseflow will be added to the model at a later phase.

HYDRODYNAMIC MODELLING

The SWMM model simulated flows and water quality to the point of entrance to the harbour. The flows, tidal boundary conditions, and physical characteristics were input to the DYNHYD model for hydrodynamic simulation of the harbour. The harbour and Hunts Bay were divided into nine segments (seven shown in Fig. 2 and two dummy segments for boundary conditions). The model simulated conditions of reverse and positive flows responding to the tidal cycle and inflows for the watershed. An example of the tidal cycle for velocity simulation is shown in Fig. 5. The model responded as expected in simulating relatively small velocities and little variation for the enclosed segment (KH7, Fig. 1), whereas the segment open to the Caribbean Sea (KH1) had higher velocities and more variation.

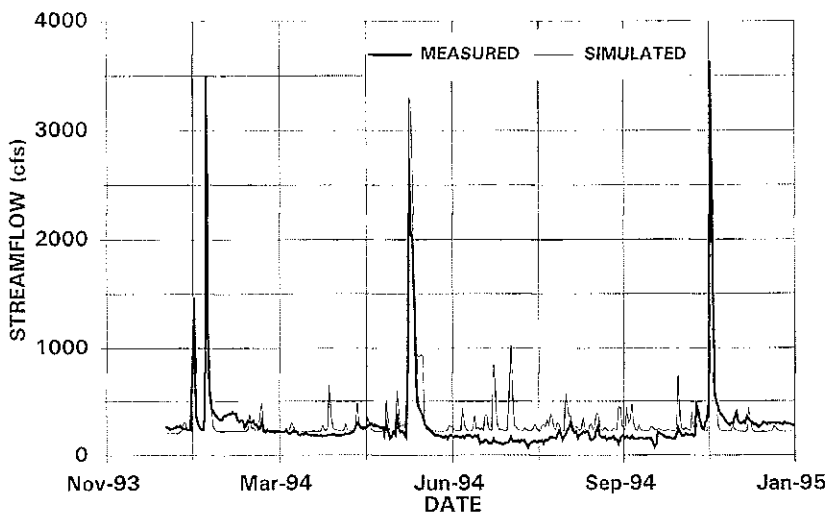


Fig. 4 Streamflow calibration.

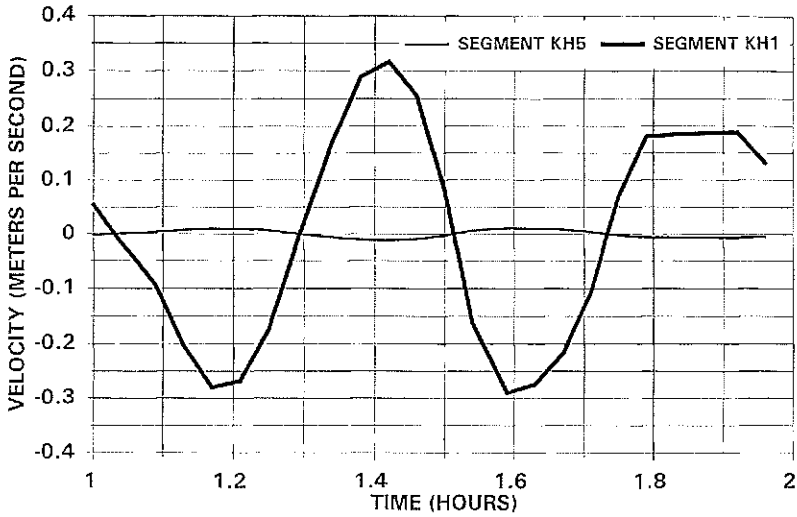


Fig. 5 Simulated velocities.

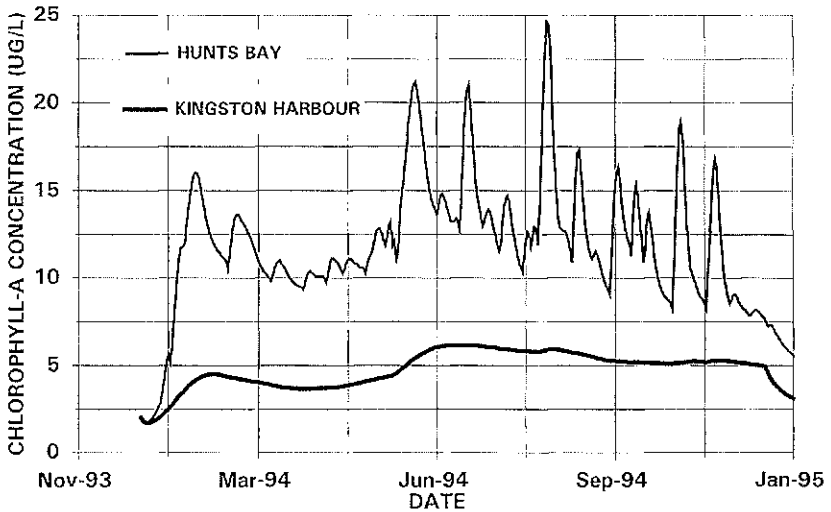


Fig. 6 Simulated chlorophyll-a.

WASP (EUTRO) MODELLING

The WASP model utilizes hydrodynamic information provided by DYNHYD and pollution inflows generated by SWMM. SWMM generated TN was assumed to consist of 5%, 50% and 45% ammonia, nitrate+nitrite and organic nitrogen, respectively. TP was assumed to consist of 50% orthophosphate and 50% organic nitrogen, respectively. Relevant model coefficients were not site-specific but were based on the author's experience in modelling tropical systems. Although data were not available for calibration, results were checked for reasonableness. For example, the simulation for Hunts Bay showed much higher concentrations of chlorophyll-a,

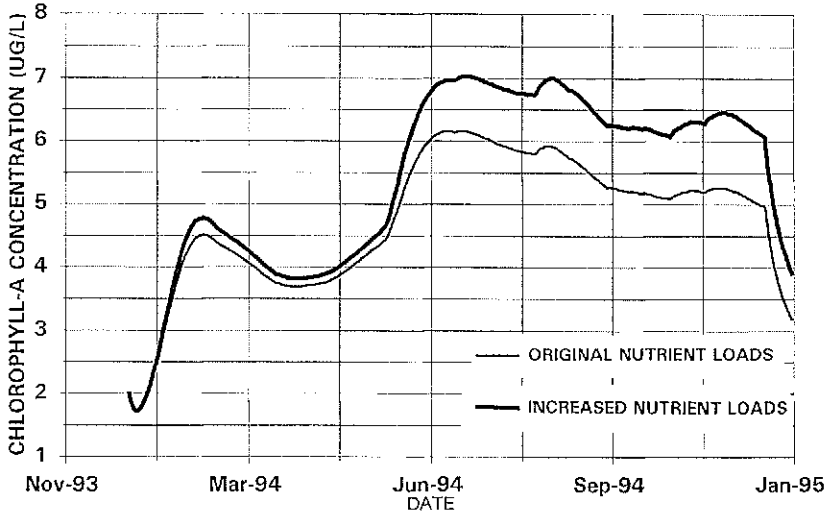


Fig. 7 Sensitivity to increased nutrient.

which for this modelling analysis is being used as an indicator of eutrophication problems. Chlorophyll-a simulation is shown in Fig. 6.

CONCLUSIONS

The preliminary modelling accomplished demonstrates that the LWWM can be used as a tool in simulating Kingston Harbour hydrodynamics and water quality. The model should be refined and expanded to its capabilities. Concurrent data of hourly rainfall, streamflow and water quality (for constituents simulated in WASP) within the watershed and harbour are desirable. Data on point source loads, groundwater quality and channel losses are also desirable. These data will allow for calibration of the model. A calibrated model will allow for development of Pollution Load Reduction Goals. For example, the model can be used to assess the impact of reducing non-point and point source loads to the harbour. Figure 7 is a demonstration of increasing nitrogen, and phosphorus loads and its resulting impact on chlorophyll-a concentration. Similarly, nutrient loads can be reduced and its impact assessed.

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