International Congress on Environmental Modelling and Software

1st International Congress on Environmental Modelling and Software - Lugano, Switzerland - June 2002

Jul 1st, 12:00 AM

A Model for Urban Stormwater Improvement Conceptualisationq

T. H. F. Wong

D. Fletcher

H. P. Duncan

J. R. Coleman

G. A. Jenkins

A Model for Urban Stormwater Improvement Conceptualisation

Tony H.F. Wong[1], *Tim D. Fletcher*[1], *Hugh P. Duncan*[2], *John R. Coleman*[3] & *Graham A. Jenkins*[4]
[1]Department of Civil Engineering, Monash University & CRC for Catchment Hydrology
[2]Melbourne Water Corporation & CRC for Catchment Hydrology
[3]CSIRO Land and Water & CRC for Catchment Hydrology
[4]School of Environmental Engineering, Griffith University & CRC for Catchment Hydrology

Abstract: Catchment urbanisation leads to increased hydraulic and pollutant loadings into receiving waterbodies. Issues concerning pollution that endangers the sustainable utilisation of water resources have focused government authorities towards integrated catchment management, where both causes and effects of pollution are addressed. Recent research has provided a platform for improving urban stormwater management. The CRC for Catchment Hydrology (CRCCH) has recently developed a Model for Urban Stormwater Improvement Conceptualisation (MUSIC), which serves as a decision support system (DSS) that packages the results of many research activities undertaken at the CRCCH and other organisations into an easily used tool. MUSIC enables urban catchment managers to (a) determine the likely water quality emanating from specific catchments, (b) predict the performance of specific stormwater treatment measures in protecting receiving water quality, (c) design an integrated stormwater management plan for each catchment, and (d) evaluate the success of specific treatment measures, or the entire catchment plan, against a range of water quality standards. This paper describes the operation of the model, the principal algorithms, and research activities undertaken in the CRC directed at further enhancing the system.

Keywords: urban stormwater quality; modelling; wetlands; bioretention; infiltration.

1. INTRODUCTION

Urban catchment managers face a complex task in assessing, prioritising, and addressing the impacts of landuse on receiving waters. The protection or restoration of urban receiving waters (waterways, estuaries and bays) involves a catchment-wide approach to flow and water quality improvement. The nature of pollutants emanating from different landuses is different and, as a consequence, treatment techniques to improve stormwater quality necessarily involve a number of measures. These treatment measures are often used in series or concurrently in an integrated treatment sequence which will improve the overall performance of the treatment system leading to a sustainable strategy which can overcome site factors that limit the effectiveness of a single measure.

Until recently, there has been inadequate information about the performance of stormwater treatment measures (eg. wetlands, bioretention systems, vegetated swales etc.). This has created uncertainty in the minds of urban catchment managers about how these treatment measures should fit together to achieve optimal cost-effective water quality outcomes. As a result, stormwater management strategies have often been based on ad-hoc, single-focus approaches.

In defining water quality management objectives, water quality standards have often tended to be event-based and deterministic, failing to recognise the stochastic nature of interactions between hydrology and the physical and biochemical processes affecting the water quality in both stormwater treatment facilities and urban receiving waters.

The Cooperative Research Centre for Catchment Hydrology (CRCCH) has recently developed a Model for Urban Stormwater Improvement Conceptualisation (MUSIC), which serves as a decision support system (DSS), addressing many of the current inadequacies, and packages many of the CRCCH research findings into an easily used tool. MUSIC is designed operate at a range of temporal and spatial scales, suitable for catchment areas from 0.01 km^2 to over 100 km^2. The modelling approach is based on continuous simulation, operating at time steps that can range from 6 minutes to 24 hours to match the spatial scale of the catchment being modelled.

MUSIC enables urban catchment managers to (a) determine the likely water quality emanating from specific catchments, (b) predict the performance of specific stormwater treatment measures in protecting receiving water quality, (c) design an integrated stormwater management plan for each catchment, and (d) evaluate the success of specific treatment measures, or the entire catchment plan, against a range of water quality standards. The model has undergone a nine month pilot testing phase amongst urban catchment managers and consultants in Melbourne and Brisbane and has recently been released to the industry as licensed freeware.

This paper describes the operation of the model, the principal algorithms, and research activities being undertaken in the CRC directed at further enhancing the system.

2. A MODEL FOR URBAN STORMWATER IMPROVEMENT CONCEPTUALISATION

2.1 Overview

Successful environmental management of urban stormwater requires understanding of :

i. relationships between rainfall and runoff in the urban context,

ii. pollutant generation from differing landuses and catchment characteristics,

iii. performance of stormwater treatment measures, and how it may vary with design specifications,

iv. long-term performance of proposed stormwater strategies against water quality standards,

v. resultant impacts on receiving ecosystems, before and after implementation of the proposed stormwater strategy.

The CRCCH developed the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) to enable research findings in its Urban Stormwater Quality Research Program to be readily disseminated to the industry. Figure 1 shows the broad framework defining the structure of the MUSIC model and the research projects undertaken by the CRCCH to continually improve the predictive capability of the model.

The adoption by industry of these research outcomes is likely to be dependent on their accessibility and ease of use. Recognising this, MUSIC has been developed for urban catchment managers to conceptualise and evaluate stormwater management systems in a holistic and integrated manner. MUSIC is a *decision support system* and is not a detailed design tool. It is one of a number of tools, which will enable users to evaluate conceptual designs of possible stormwater management systems for their catchments to meet pre-specified water quality objectives, and to derive indicative sizes of the various stormwater quality treatment facilities selected.

The process by which the user configures a stormwater treatment strategy is based on a simple icon-driven interface (see Figure 5). The user configures the proposed stormwater management strategy on a map or plan, creating a 'treatment train' of stormwater treatment and reuse measures. MUSIC will simulate the performance of the proposed strategy on a continuous basis using historical and/or stochastically generated data of flow and pollutant concentration.

The performance of the stormwater treatment train can be examined via a range of output options, including time-series graphs of flows and pollutant loads or concentrations, statistical summaries, or cumulative

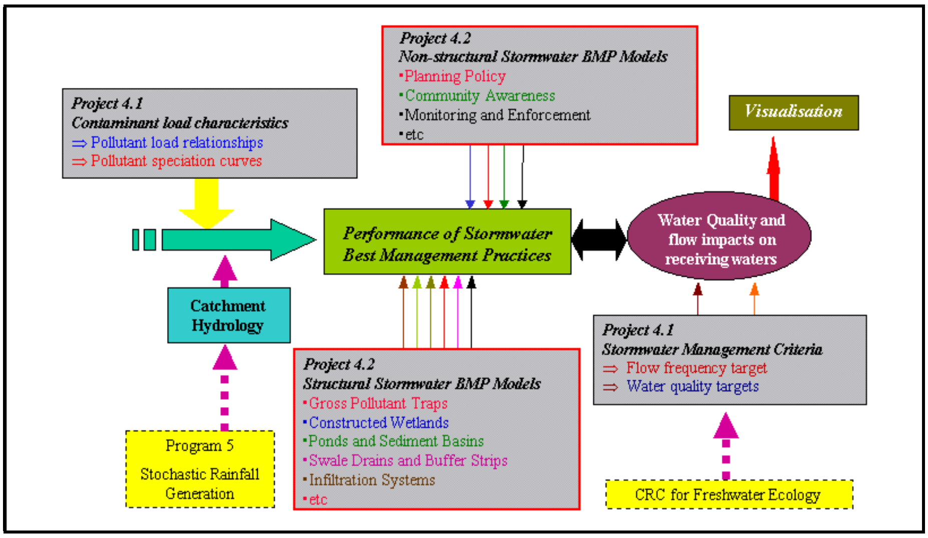


Figure 1 Framework of the MUSIC Model and associated CRCCH research

probability plots (Figure 2). Water quality standards can be applied to any of these outputs to allow easy interpretation of performance. Output can also be exported, for use in other software (eg. statistical analysis software).

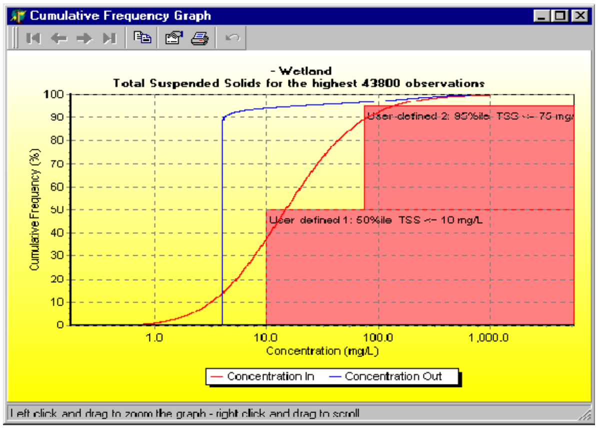


Figure 2 Cumulative probability plot output, showing water quality standard (shaded box).

2.2. Modelling Catchment Hydrology

The majority of stormwater runoff in urban catchments is generated from the impervious surfaces. Baseflow, influenced by sub-surface soil moisture and groundwater levels, is less dominant in urban catchments as evident by the "flashy" nature of urban stormwater hydrographs.

The algorithm adopted to generate urban runoff is that developed by Chiew *et al.* [1997], which is based on a simplified model involving definition of the impervious area and two soil moisture storages, ie. the shallow and deep soil moisture storages, as shown in Figure 3. That model, which was initially developed as a daily model, was modified to enable disaggregation of the generated daily runoff into sub-daily temporal patterns.

Runoff routing through the catchment is undertaken using the Muskingum-Cunge flood routing algorithm.

2.3 Modelling Water Quality Generation and Treatment

Total Suspended Solids (TSS), Total Phosphorus (TP) and Total Nitrogen (TN) concentrations generated from urban, agricultural and forested catchment are generated using a stochastic process involving cross correlation (between TSS and TP) and serial correlation of water quality time series. Pollutant generation rates are based on statistical analysis of urban stormwater pollutants by Duncan [1999].

MUSIC simulates the performance of stormwater treatment measures using the USTM in a two-stage process. The hydrodynamic behaviour of the stormwater treatment facility is first modelled by

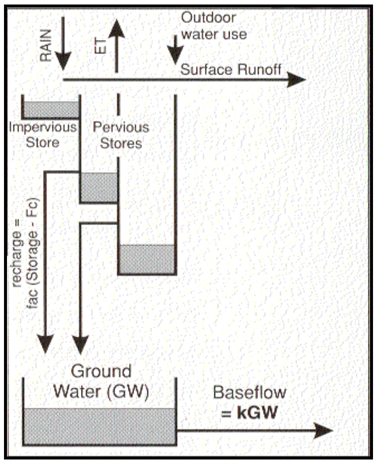


Figure 3 Conceptual Rainfall-Runoff Model adopted for MUSIC (after Chiew et al., 1997)

describing this behaviour as a series of well-mixed waterbodies notionally located within the physical configuration of the stormwater treatment system. The pollutant reduction within each of these well-mixed waterbodies is then computed using a first-order decay algorithm. These two processes are described below.

2.4 Hydraulic Efficiency of Stormwater Treatment Systems

As stormwater moves through the treatment facility it tends to spread out due to turbulence and other hydrodynamic effects even under ideal flow conditions. This behaviour can be modelled quite closely by a series of well-mixed waterbodies or Continuously Stirred Tank Reactors (CSTR). The number of CSTRs used has a large effect on the modelled behaviour. A single CSTR models a tank or pond in which the inflow is immediately and completely mixed with the existing contents. A sedimentation pond or gross pollutant trap may approach this condition. A string of many CSTRs in series mimics plug flow with only limited dispersion, such as might occur in a long vegetated wetland or swale. The number of CSTRs (N) can be related to the short-circuiting parameter (n) of Fair & Geyer [1954] or the hydraulic efficiency (λ) of Persson *et al.* [1999], ie.

$$N \sim \frac{1}{1-n}; \qquad N \sim \frac{1}{1-\lambda}$$

Persson, *et al.* [1999] undertook a series of two-dimensional hydrodynamic modelling to derive λ values for a number of typical pond or wetland shapes with different inlet/outlet and length to width configurations as illustrated in Figure 4.

2.5 The k-C* Model

When a parcel of water carrying pollutants moves from one CSTR to another, the water quality of the parcel is influenced by several physical processes, and the

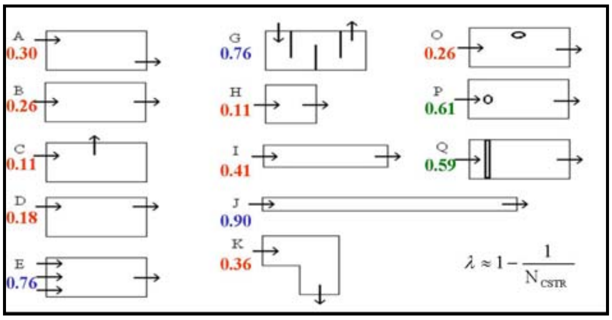


Figure 4 Hydraulic efficiencies (λ) of detention systems

detailed behaviour can be very complex. But the overall effect is that contaminant concentrations in the parcel tend to move by an exponential decay process towards an equilibrium value for that site at that time. This behaviour can be described by the first order kinetic (or k-C*) model as expressed in equation (1), in which C* is the equilibrium value or background concentration, and k is the exponential rate constant.

$$C_{out} = C^* + (C_{in} - C^*)e^{-k/q} \qquad (1)$$

where C^* = background concentration (mg/L),
C_{in} = input concentration (mg/L),
C_{out} = output concentration (mg/L),
k = (decay) rate constant (m/y)
q = hydraulic loading (m/y)

The USTM utilises this first-order kinetic decay model to simulate the behaviour of pollutants as they pass through each CSTR of the treatment measure being modelled. This model has commonly been used in predicting the performance of wastewater treatment facilities (Kadlec and Knight, 1996), and is now being applied in stormwater and combined sewer treatment (Wong and Geiger, 1997, Wong *et al*., 1999; Wong *et al*., 2001). Contaminant reduction by the k-C* model is calculated separately at each timestep for each CSTR.

The rate of decay, k, and the background concentration, C*, are both influenced by the pollutant characteristics, particularly particle size and settling velocity distributions. It is therefore apparent that a treatment measure that targets large particles (such as a sedimentation basin) will have a high decay rate (because large particles settle quickly). They will also have a high background concentration (because the finer particles are kept in suspension by the typically high flow velocities and short detention times in such measures). There is a theoretical link between the parameter k and the settling velocities of suspended particles in the waterbody.

Refinement of the parameters for the k-C* model, to suit local conditions (particle size distributions in particular) and treatment measure design specifications, is currently being undertaken. Intuitively, the parameter C* can be expected to vary with discharge (ie. associated with the input of energy to re-suspended deposited fine particulates) and the influence of biological and chemical processes operating during the inter-event period. Similarly, field investigations have indicated that despite its theoretical link to settling velocity, the parameter k does not necessarily match the settling velocity of the target pollutant size, especially for very fine particulates (eg. < 40 um) or when the primary treatment process is associated with filtration rather than sedimentation.

3. APPLICATION OF MUSIC

To date, MUSIC has been pilot-tested by Melbourne Water Corporation, Brisbane City Council and several consultants and has been used to aid in their development of stormwater management schemes in greenfields, as well as in assessing development applications. The use of the model has provided these organisations with a rigorous basis for assessing the performance of treatment trains. Through modelling, it is now possible to ascertain the relative merit of a number of stormwater treatment measures configured in series.

3.1 Case Study

A case study was prepared to demonstrate the application of MUSIC and involves the formulation of a stormwater quality improvement strategy for a built-up area in an Australian city. The area has been serviced by traditional stormwater infrastructure (eg. underground pipes, hydraulically effective connections of impervious surfaces to the stormwater drainage system etc) but has a network of public open space, located along the waterway corridors. There is a flood retarding basin on one of the major watercourses which is only engaged during large events, with a low flow pipe by-passing the basin during for frequent storm events.

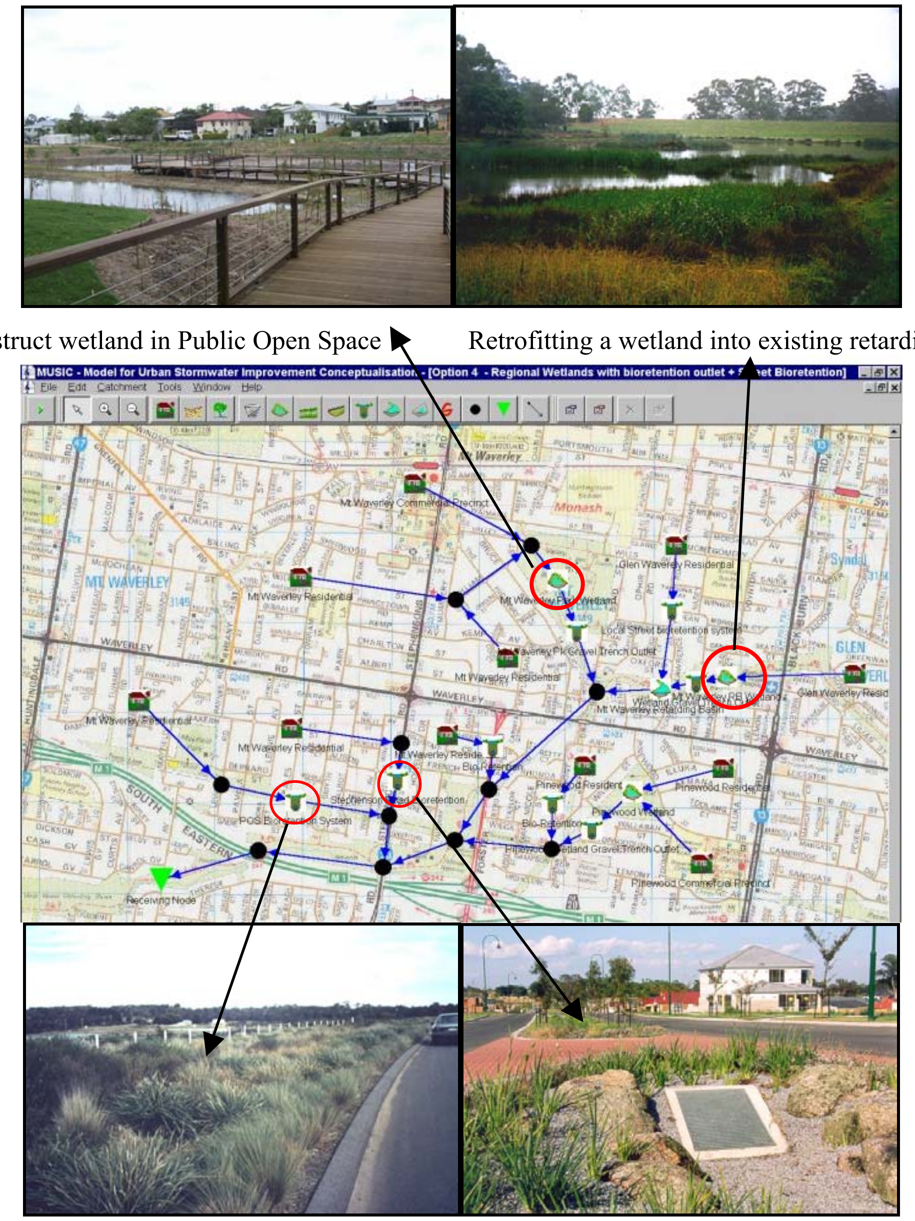
A number of options for retrofitting stormwater quality improvement measures were investigated using MUSIC. The existing conditions of the catchment and four possible stormwater quality management options were simulated. The four options considered are as follows:-

1. Retrofitting a stormwater treatment wetland onto an existing retarding basin;
2. Option 1 + construction of a further two wetlands on public open space;
3. Option 2 + construction of bioretention systems and vegetated swales along major roads and on multiple-use corridors;
4. Option 3 + construction of bioretention systems to further treat stormwater discharge from the three wetlands.

Figure 5 shows the layout of the model established for Option 4 together with pictorial representations of the proposed treatment measures. The use of constructed wetlands, ponds, vegetated swales and bioretention systems for stormwater quality improvement are becoming popular urban design strategies for ecological sustainable developments (Wong, 2001).

Assessment of the performance of the stormwater management options examined is based on two forms of considerations. From a regional perspective, the reduction in the mean annual load of stormwater pollutants (eg. TSS, TP and TN) will be the primary management objectives. However, for the protection of ecosystem health of the local waterways, consideration of the cumulative probability plots of mean daily concentrations will also need to be required. Figures 6 and 7 show the typical results of the simulations.

From Figure 6, it is evident that the adoption of Option 1, associated with the retrofitting of a stormwater treatment wetland onto an existing retarding basin would yield approximately 25% reduction in TSS, 15% reduction in TP and 8% reduction in TN. The construction of two further regional wetlands will result in further reduction in the mean annual load. The water quality improvement measures identified for this built-up area can be expected to deliver approximately 49% reduction in TSS, 38% reduction in TP and 25% reduction in TN if they were to be implemented in their entirety



Construct wetland in Public Open Space | Retrofitting a wetland into existing retarding basin

Vegetated swales for stormwater conveyance | Bioretention systems along road median

Figure 5 MUSIC model showing stormwater treatment strategy for a built-up area

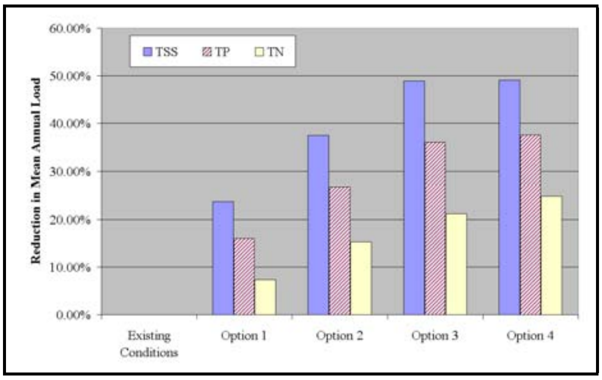


Figure 6 Percentage reduction in mean annual loads of stormwater pollutants.

Only a very marginal incremental reduction in pollutant is gained when progressing from Option 3 to Option 4. Option 4, which involves the incorporation of bioretention systems to the outlets of the regional wetlands, was introduce in an effort to comply with the water quality (concentration) standard for the local watercourse. As evident in Figure 7, the works in Option 3 were not sufficient to satisfy the water quality objectives for TN stated for the case study, ie. that the 50 percentile mean daily concentrations of TN should not exceed 0.65 mg/L. Some further reduction of the outflow from the wetlands was found to be necessary to enable compliance of this water quality criterion.

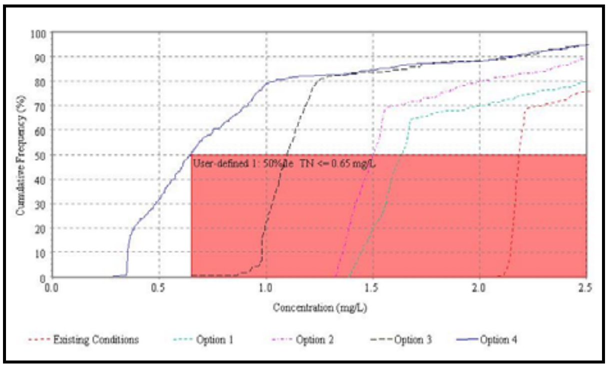


Figure 7 Cumulative probability curves for TN concentrations.

5. CONCLUSION

There have been several major impediments to the effective design, prioritisation and evaluation of urban stormwater treatment strategies. These stem from uncertainties about the likely water quality from catchments of different landuse, uncertainties about the performance of stormwater treatment measures, particularly when combined in parallel or series, and an inability to compare the performance, benefits and costs of alternative stormwater treatment strategies.

The development of MUSIC overcomes many of these limitations, and provides urban catchment managers with an easy to use decision support tool by which they can evaluate and compare alternative strategies aimed at protecting aquatic ecosystems from the impacts of urbanisation. The results of MUSIC simulations can be used to inform the decision making process associated with the economic risk analysis, prioritising and staging of the stormwater quality management strategy for the catchment.

Catchment managers in Australia are now adopting the model to assist with both their strategic catchment planning as well as their assessment of urban development applications submitted by land developers.

6. REFERENCES

Chiew, F.H.S., L.B. Mudgway, H.P. Duncan, and T.A. McMahon, Urban Stormwater Pollution, Industry Report 97/5, Cooperative Research Centre for Catchment Hydrology, July 1997.

Duncan, H. P., Urban Stormwater Quality: A Statistical Overview, Report 97/1 Cooperative Research Centre for Catchment Hydrology. Melbourne, 1999.

Fair, G.M. and J.C. Geyer, Water Supply and Waste Disposal, John Wiley and Sons, New York, Vol. 2, 973pp, 1954.

Kadlec, R.H. and R.L. Knight, Treatment Wetlands. Boca Raton, Florida, CRC Press, 1996.

Persson, J., N.L.G. Somes, and T.H.F. Wong, Hydraulics Efficiency of Constructed Wetlands and Ponds, Wat. Sci. Tech.,Vol 40, No.3, pp. 291-300, 1999.

Wong, T.H.F., A Changing Paradigm in Australian Urban Stormwater Management, keynote address, 2nd South Pacific Stormwater Conference, Auckland, New Zealand, 27 – 29 June, 2001.

Wong, T.H.F., H.P. Duncan, T.D. Fletcher, G.A. Jenkins and J.R. Coleman, A unified approach to modelling urban stormwater treatment, 2nd South Pacific Stormwater Conference, Auckland, New Zealand, 27 – 29 June, 2001, pp 319 - 327, 2001

Wong, T.H.F. and W.F. Geiger, Adaptation of Wastewater Surface Wetland Formulae for Application in Constructed Stormwater Wetlands, Ecological Engineering, Vol. 9 No. 3, pp 187-202, 1997.

Wong, T.H.F., A. Rodder and W.F. Geiger, Predicting the Performance of a Constructed Combined Sewer Overflow Wetland. Proceedings of the Eighth International Conference on Urban Storm Drainage, Sydney, Australia: pp 1947-1954, 1999.