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SUMMARY

The results of testing the Storm Water Management Model (SWMM) on a number of urban test catchments are presented. The runoff quantity subroutine was tested and good results were obtained on eight catchments. The SWMM runoff quality subroutine was tested on three catchments only. The lack of data allowed only a qualitative discussion of the quality results obtained.

INTRODUCTION

Rapid advances in urban hydrology led to the development of a large number of urban runoff models in recent years, but only in the last three years have several comparative studies of various urban runoff models been undertaken to assist model users in model selection. Among these studies, the most notable were those sponsored by the Environmental Protection Agency[1] and the Canadian Department of Environment[10]. As a result of these studies, the Canadian Urban Drainage Subcommittee decided to adopt the SWMM model of US.EPA for further study, modification and application in urban runoff studies in Ontario. Some of the questions raised during this process were those of reliability of the SWMM model, the conditions under which the model could fail, and the accuracy of the SWMM simulations. All these questions are of utmost importance in planning and design of urban drainage systems.

When the SWMM model was developed, very little urban runoff data was available for model testing and verification. Consequently, only a limited testing of the model was carried out on four catchments and the limited data available allowed only a qualitative evaluation of the SWMM simulations[1,3]. Since then, several more extensive studies have been carried out on urban test catchments and the results were reported by Heeps and Mein[4], Jewell et al.[5], Marsalek et al.[6], Preul and Papadakis[9], and Shubinski and Roesner[11]. In all these cases, the number of test catchments was limited.

In this paper, the results of the SWMM model testing on a number of new test catchments are reported and a correlation between the accuracy of field observations and the accuracy of model simulations is demonstrated for runoff quantity.

METHODOLOGY FOR TESTING RUNOFF MODELS

When testing conceptual runoff models, the model tested is used to simulate the observed phenomena and the goodness of fit of the simulations to the observations is then evaluated. A set of criteria for evaluating the goodness of fit has to be devised and applied.

Modelling Errors

There is a number of sources of error causing the differences between the observations and simulations. These error sources include the following:

1. Bias in the simulated output (i.e. flows and their quality) because of incomplete or biased model structure.
2. Bias in the simulated output because of random or systematic errors in the input data (e.g. precipitation, catchment characteristics).
3. Random and systematic errors in the observed output (flows and their quality) used for comparisons with the simulated output.
4. Bias in the simulated output because of an incorrect application of the model (e.g. poor catchment discretization, selection of time steps, etc.).
5. Errors in the simulated output caused by an erroneous model calibration.

When testing conceptual models and their accuracy, it becomes extremely difficult to separate the effects of individual sources of error and to determine their contribution to the overall error. The last two errors, i.e. those caused by incorrect model application and calibration, can be significantly reduced and are eliminated here from further consideration. The errors due to uncertain input and output data (observations) are grouped here together and their effect on the accuracy of model simulations will be studied by statistical methods.

Selection of goodness of fit criteria

Runoff quantity. Numerous criteria of goodness of fit have been proposed for runoff models. For a review of some of these criteria, a reference is made to Fleming's work[2]. Fleming concluded, that no research has been undertaken to compare the various criteria available, and therefore, one can not define the best criteria for hydrologic modelling. He also suggested that the criteria should evaluate the following three parameters of a runoff hydrograph: the total runoff volume, the peak flow and the time to peak. Consequently, the following three rather simple criteria were selected for use in this study:

a)Runoff volumes - the ratio of volume observed and volume simulated

b)Runoff peaks - the ratio of peak observed and peak simulated

c)The time to peak - the ratio of the time-to-peak observed and time-to-peak simulated.

Runoff quality. The assessment of runoff quality simulations is even less developed than that of quantity simulations. From the runoff management point of view, the criteria can be defined for each constituent similarly as it was done for the quantity, i.e. describing the constituent pollutograph by the following three parameters:

a)The total constituent emission
b)The peak constituent concentration
c)The time to peak concentration.

These goodness of fit criteria for runoff quantity and quality were then used on the test catchments studied.

URBAN TEST CATCHMENTS

Description of Data Collection Projects

The Urban Drainage Subcommittee has obtained urban runoff data from a number of test catchments. These catchments and their basic characteristics are listed in Table 1.

Catchment name	Location	Sewer System
Bannatyne	Winnipeg, Man.	Combined
Brucewood	Toronto, Ont.	Separate
Calvin Park	Kingston, Ont.	Separate
East York	Toronto, Ont.	Separate
Halifax	Nova Scotia	Combined
Hamilton	Ontario	Combined
Malvern	Burlington, Ont.	Separate
Toronto-West	Ontario	Combined
Toronto-East	Ontario	Combined

Catchment name	Phenomena monitored			Area Size (acres)	Reference
	Precip.	Runoff	Quality		
Bannatyne	x[a]	x[a]	x[a]	542	14
Brucewood	x	x	x	48	14
Calvin Park	x	x		89	10
East York	x	x	x	40	16
Halifax	x	x		168	15
Hamilton	x[b]	x[b]	x[b]	176	3
Malvern	x	x	x	58	7
Toronto-West	x[a]	x[a]		2330	14
Toronto-East	x[b]	x[b]	x[b]	338	8

[a] limited number of events

[b] projects started recently, no data available as yet

Table 1. Urban Test Catchments.

The test catchments cover a wide range of catchment sizes (40 acres to 2300 acres) as well as of residential developments. Brucewood, Calvin Park and Malvern represent modern residential areas served by separate sewers. Bannatyne, Halifax, Toronto-West and Toronto-East are older residential areas served by combined sewers. East York is an older area on which the sewers were separated only recently. The storm sewers receive runoff mostly from roads and side-walks. The roof drains are connected to the old combined sewer.

On all the areas, precipitation and runoff were monitored. Quality data were collected with a various degree of success on all the areas except for Calvin Park and Toronto-West.

All of the projects are not at the same stage. The Brucewood and Bannatyne projects have been discontinued. The remaining data collection projects are continuing to a various extent although the data collected in East York have not yet been fully analyzed, and the Hamilton and Toronto-East projects which started only recently have as yet no significant data.

Some results from a previous study[10] with the SWMM model on two additional urban catchments (Oakdale, Chicago and Gray Haven, Baltimore) were also included. Thus for runoff quantity simulations, the data for the following eight areas were available for the testing of the SWMM model: Bannatyne, Brucewood, Calvin Park, Halifax, Malvern, Oakdale, Gray Haven and Toronto-West.

The runoff quality data are much less plentiful. In fact, only limited data and quality simulations were available for the Bannatyne, Brucewood and Malvern catchments.

Uncertainty in the collected data

A quantitative evaluation of uncertainties in the collected data was not possible due to the lack of information. Therefore, only a qualitative evaluation was made here, the uncertainty in the data was ranked and this ranking was then used in a later part of this study. The ranking of the data from the eight areas under consideration is shown in Table 2, where a low rank number indicates the better data set.

AREA	Rank
Bannatyne	7
Brucewood	5
Calvin Park	1-3 (assigned aver.rank=2)
Halifax	6
Gray Haven	1-3 (2)
Oakdale	4
Malvern	1-3 (2)
Toronto-West	8

Table 2. Ranking of data uncertainties for the studied urban areas.

The Calvin Park, Gray Haven and Malvern data were given the highest rank. In all these cases, the catchments were well defined and surveyed, the precipitation was measured on the catchment, and checked against another gauge, flows were measured by calibrated constriction flow meters, a good synchronization of precipitation and runoff records was evident. The measured data were checked for correctness.

The Oakdale and Brucewood data were rated slightly lower. It would appear that the flow meters were not calibrated and there is no evidence that the collected data were checked. It was expected that the data from the smaller Oakdale catchment were better defined (more accurate) than those from the Brucewood catchment.

The next data ranked are the Halifax data collected on an older area with some uncertainties in the catchment imperviousness. Otherwise, the instrumentation system is fairly good; a raingauge is located within the catchment and flows are measured by a critical flow meter.

The lowest rated data were those collected on the Bannatyne and Toronto-West catchments. There were no rain data collected directly on the Bannatyne catchment. Consequently, the data from some nearby rain gauges had to be used. In the case of Toronto-West, the flow rates were only inferred from the depth of flow measurements and the Manning equation. Only one raingauge was used to measure the precipitation.

DISCUSSION OF RESULTS

Runoff quantity

The results of runoff quantity simulations with the SWMM model are given in Table 3. For runoff volumes, peak flows, and times to peak, the ratios of observed to simulated values were computed. The results were described by the mean value of these ratios, standard deviation about mean and the percentage of simulations for which the simulated values were within ±20% of the observed ones (see Table 3).

	Runoff volumes — Ratio $Vol._{obs.}/Vol._{sim.}$		
	average	standard deviation	% of simulations within ± 20% of observations
Bannatyne	1.40	0.34	24%
Brucewood	0.91	0.19	66%
Calvin Park	1.03	0.17	75%
Gray Haven	—	—	—
Halifax	1.01	0.14	85%
Oakdale	—	—	—
Malvern	1.01	0.12	89%
Toronto-West	0.87	0.26	50%

	Runoff peak flows Ratio $Qp_{obs.}/Qp_{sim.}$		
	average	standard deviation	% of simulations within ± 20% of observations
Bannatyne	1.12	0.09	81%
Brucewood	1.22	0.26	42%
Calvin Park	1.09	0.16	72%
Gray Haven	0.98	0.24	61%
Halifax	0.78	0.22	44%
Oakdale	1.04	0.19	70%
Malvern	1.05	0.16	77%
Toronto-West	1.12	0.14	70%

	Times to peak Ratio $Tp_{obs.}/Tp_{sim}$		
	average	standard deviation	% of simulations within ± 20% of observations
Bannatyne	0.98	0.12	90%
Brucewood	0.91	0.10	87%
Calvin Park	0.93	.09	92%
Gray Haven	1.02	0.05	100%
Halifax	1.11	0.21	60%
Oakdale	0.92	0.13	81%
Malvern	0.96	0.07	99%
Toronto-West	1.13	0.22	55%

Table 3.SWMM runoff quantity simulations-goodness of fit.

For runoff volumes, the best goodness of fit was obtained for the Malvern catchment - nearly 90% of all the simulated volumes were within the ±20% limits. For peak flows, the best fit was found for the Bannatyne catchment, 81% of all simulations were within the above accuracy limits. Finally, for the times to peak, the best fit was found for the Gray Haven catchment, practically all the simulations were within the above accuracy limits. The overall goodness of fit was also evaluated. The Malvern catchment ranked the highest, the Toronto-West data ranked the lowest.

A large variation in the goodness of fit of the SWMM simulations on the test catchments led to a question of whether there is a correlation between the uncertainty in the input data and the goodness of fit. Since the data on hand did not allow the use of parametric statistics, this question was studied using non-parametric statistical methods. The null hypothesis was defined as follows: There is no correlation between the uncertainty in the input data and the goodness of fit of simulated to observed data. This would imply that the errors in the simulations are caused by a biased model structure.

The above null hypothesis was tested using the Spearman rank correlation coefficient. The calculation is given in Table 4.

Test catchment	Input data uncertainty rank	Goodness of fit rank (after Table 3)	Difference
Bannatyne	7	5	2
Brucewood	5	6	1
Calvin Park	2	3	1
Gray Haven	2	2	0
Halifax	6	7	1
Oakdale	4	4	0
Malvern	2	1	1
Toronto-West	8	8	0

$$\Sigma d_i^2 = 8$$

$$r_s = \frac{\Sigma x^2 + \Sigma y^2 - \Sigma d_i^2}{2\sqrt{\Sigma x^2 \Sigma y^2}} = \frac{73.0}{80.9} = 0.90$$

Table 4. Ranking of input data uncertainty and the goodness of fit.

For eight observations, the value of Spearman rank correlation coefficient of 0.90 is significant at the 0.01 level of confidence[12] and the null hypothesis has to be rejected. Thus there is a correlation between the uncertainty in the input data and the goodness of fit of the SWMM runoff quantity simulations. This indicates, that lower simulation accuracies obtained with the SWMM model on some areas, e.g. Toronto-West, are not necessarily caused by the modelling bias, but rather by inaccurate input data. A rigorous evaluation of the input data errors could not be done for any of the studied areas, since this would require much more extensive data records than those available (e.g. several precipitation records, etc.). Only on a thoroughly instrumented area one could directly separate the modelling bias errors from those caused by the input data errors.

One condition, under which the SWMM model fails, is the surcharged flow in sewers. A technique in which the sewer surcharging was avoided by arbitrarily increasing the sewer pipe capacity was used by Waller[15] in conjunction with the SWMM model on the Halifax catchment. As one would expect, it led to an overestimate of peak flows and a shortening of times to peak. These results, however, were more realistic than the truncated hydrographs produced by the normal SWMM runoff subroutine.

Runoff quality

Only limited runoff quality data have been collected on the studied areas so far and not all of these data have been processed to this date. In fact, quality data were available only for the following three catchments: Brucewood, Bannatyne, and Malvern. These data do not allow proper statistical analysis as was done for the quantity data. Consequently, only a qualitative discussion of the processed data follows.

The runoff quality data and the SWMM simulations are given in Table 5. The ratios of observed to simulated values were calculated for the total pollutant emissions and peak concentrations. For individual catchments, these ratios were characterized by the mean values.

	Bannatyne ISS=0	Bannatyne ISS=1	Brucewood ISS=0	Brucewood ISS=1	Malvern ISS=0
(a)					
Total BOD obs. / Total BOD sim.	3.10	5.25	.66	.29	--
Total SS obs. / Total SS sim.	1.34	2.20	6.43	.46	4.12
Total COD obs. / Total COD sim.					.49
Total N obs. / Total N sim.					4.80
Total P obs. / Total P sim					2.45
(b)					
Peak BOD obs. / Peak BOD sim.	2.90	6.43	1.58	1.35	--
Peak SS obs. / Peak SS sim.	1.05	--	9.60	.43	5.48
Peak COD obs. / Peak COD sim.					.28
Peak N obs. / Peak N sim.					3.82
Peak P obs. / Peak P sim.					3.01
Reference	14		14		7

Table 5.SWMM model runoff quality simulations described by mean values of the ratios (a) Total constituent emission observed to that simulated (b) The peak constituent concentration observed to that simulated.

The Brucewood and Malvern catchments are relatively clean areas, served by separate sewers. The observed Biochemical Oxygen Demands (BOD) for minor storms did not exceed 25mg/litre, the observed Suspended Solids (SS) concentrations did not exceed the value of 500 mg/litre. A large scatter in the observed and simulated data comparisons was evident. No conclusions can be drawn regarding the use of the options to calculate the suspended solids. The exponential decay option (code ISS=0) yielded simulated concentrations that were too high; the other option (an empirical relationship, code ISS=1) yielded simulated concentrations that were too low. On average, the calculated BOD concentrations were underestimated. The estimate of the suspended solids concentrations depended on the selection of the calculation option.

The concentration of Nitrogen and Phosphates were on average underestimated in the SWMM simulations. On the other hand, the Chemical Oxygen Demands (COD) were consistently overestimated in the simulations. It is expected that these runoff quality data will be further analyzed and attempts will be made to explain the lack of goodness of fit.

The Bannatyne catchment is served by combined sewers. Unusually high values of BOD and SS concentrations were observed on this area. As indicated in Table 5, the SWMM simulations underestimated the total BOD and SS emissions as well as the peak concentrations of both BOD and SS.

Uncertainties in the collected runoff quality data cannot be estimated and in fact, they could be fairly high. Consequently, one cannot conclude, if the errors are due to modelling bias or due to errors in the quality data. It may take another one or two years before a sufficient volume of runoff quality data is accumulated under the present program and a full evaluation of the SWMM quality subroutine is possible. Meantime, the runoff quality data obtained with the SWMM should be accepted and used only with great caution.

CONCLUSIONS

The runoff quantity subroutine of the Storm Water Management Model was tested with a good success on a number of new urban test catchments. The goodness of fit of the simulated to the observed data was found to be dependent on the uncertainty in the input data. No presently instrumented catchment allows separation of the errors due to the modelling bias from those due to the uncertainty in the input data. On the best instrumented catchment, fairly accurate results were obtained with the SWMM model. In fact, up to 90% of runoff volumes, 77% of runoff peak flows and 100% of times to peak were simulated with an accuracy better than ±20% of the observed values.

The SWMM model runoff quality simulations were found to be less satisfactory. Though the insufficient data prevent drawing any firm conclusions, it appears that the quality subroutine is not readily applicable to all urban catchments. The SWMM quality simulations should be treated with great caution, particularly if used for a selection of urban runoff control alternatives, or policy enforcement. It may require another one or two years of data collection before the SWMM quality subroutine can be fully evaluated for the feasibility of application on Canadian urban catchments.

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