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AN INVESTIGATION OF CURVE NUMBER APPLICABILITY TO WATERSHEDS IN EXCESS OF 25000 HECTARES (250 KM^2)

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The objective of this study was to apply a continuous hydrologic model that uses the Curve Number method to a large undeveloped watershed, calibrate the model and obtain parameter values; and, from the acquired information, to attempt to determine the general applicability of the Curve Number method to large watersheds. The results are generally favorable, with simulated flow results typically close to actual recorded values of flow. The general results of flow simulation are within 8 percent (simulated flow versus recorded flow). Given the number of potential sources of error other than catchment size, these results tend to indicate the appropriateness of the model for use on these study watersheds, as well as its applicability to other large watersheds.

INTRODUCTION

The application of hydrologic models to physical systems is a powerful tool for various purposes, but the actual applicability of said models to a specific watershed must be known before a model can be used appropriately. That is, the question "*Can the model be used on the study watershed and be expected to give usable results?*" must be answered before a model can be chosen for a specific watershed.

One consideration of a model's applicability is the *size of the watershed*. Various methods of runoff calculation are available, including the United States Soil Conservation Service (SCS) method and the various models that use it in their calculations. One such model that uses a modified SCS method is QUALHYMO. Because the SCS method was developed using test plots of small size, the application of this model to watersheds of any size larger than those used to determine the original relationships of the method is a potential cause for concern. Investigation to determine whether such an application is possible is warranted.

SCS CN PROCEDURE

In the 1950's, the SCS was given the task of developing a system to relate the amount of surface runoff from rainfall to soil cover complexes. The underlying theory of the SCS-CN procedure is that runoff can be related to soil cover complexes and rainfall through a parameter known as a Curve Number (CN). The physical processes involved are: that before runoff can occur, rainfall must exceed the infiltration capacity of the soil and any initial abstractions in the watershed, that is runoff begins after some rainfall has accumulated, and then becomes asymptotic to a 45 degree line. The basic mathematical relationship is that the ratio of actual retention to potential retention is equal to the ratio of runoff to rainfall minus initial abstraction:

$$Q/(P-Ia) = F/S \qquad (1)$$

where

Q = runoff,

P = precipitation,

Ia= initial abstraction,

F = cumulative infiltration,

S = maximum retention.

After runoff begins, all rainfall becomes either runoff or retention and for all practical purposes both sides approach unity as $P \rightarrow \infty$. Field data indicated that initial abstraction is approximately equal to 0.20 of storage and the equation then becomes:

$$Q = (P-0.2S)^2 /(P + 0.8S) \text{ , for } P > 0.2S \qquad (2)$$

By reducing the relationship to only one parameter, S, it was possible to develop the Curve Number concept. SCS developed a relationship between storage, S, and CN, by a simple relation designed to give a CN range of 0 to 100. The relationship was established as:

$$CN = 1000/(10 + S)\text{(imperial units)} \qquad (3)$$

$$CN = 25400/(254+S)\text{(metric units)} \qquad (4)$$

The assignment of curve number values to soil cover complexes was achieved by a combination of empirical data fitting and interpolation. Data were plotted as rainfall versus runoff (P versus Q) and overlain with plotted curve numbers for Ia = 0.2S, and the median curve number was selected. The curve numbers thus represent the averages of the median site values for hydrological soil groups, cover, and hydrologic conditions. Thus, the runoff for a given soil cover complex can be estimated by knowing the CN (from lists provided by the SCS) and the precipitation for the event under consideration, via the use of equations 2 and 3 or 2 and 4. The runoff then becomes a direct function of rainfall and CN.

Because the occurrence of infiltration reduces the potential storage capacity of a soil profile, a means to account for the change in S must be considered. In the SCS method, the change in CN (which is related to the change in S) is based on an antecedent moisture condition (AMC) determined by total rainfall in the five days preceding the storm. The SCS developed three distinct classes or levels of AMC: AMC-I (dry conditions) being assigned as the "lower limit of moisture or upper limit of S", AMC-III (wet conditions) is the "upper limit of moisture or the lower limit of S", and AMC-II considered as the average soil moisture condition (Soil Conservation Service, 1972). As a result of there being only distinct classes, there resulted in turn only discreet values of CN values rather than a continuum.

In essence, the SCS CN procedure involves describing the soil cover complex and deriving the corresponding CN value from SCS tables (National Engineering Handbook, Section 4, Table 9.1), providing data about the AMC (I, II, or III), and using data on the rainfall volume for the storm in question. The SCS CN procedure is a lumped approach to rainfall-runoff, in that it does not consider time in the calculations: there is an input value of rainfall, and an output value of runoff (Hope, 1981; Hawkins, 1978).

Since its development in the 1950's, the curve number procedure has become widely used in hydrology. In fact, it has been overused and has been applied to situations and conditions for which it was not designed. Ponce (1989) writes that:

> "its indiscriminate use for catchments in excess of 250 km^2 ... without catchment subdivision is generally not recommended. The runoff curve number was originally developed by SCS for use in midsize rural watersheds ... therefore its extension to large basins requires considerable judgment".

However, the CN procedure is still a valuable predictive tool when used for the type of problems it was developed for, that is, evaluating effects of land use changes and conservation practices on direct runoff (Rallison, and Miller 1981).

MODEL USED

QUALHYMO is a continuous, lumped, deterministic, quantity and quality hydrologic model. Release 2.2a uses a modified SCS S* procedure to model direct runoff quantity from pervious areas, and a volumetric coefficient approach for impervious areas (Rowney, 1992). The model's primary function is in the analysis of surface runoff and pollutant changes as a result of changes in land use. It can be used in watershed development studies for either small rural watersheds or large urban watersheds.

The modified S* method also uses the SCS CN equation of direct runoff, equations 1 and 2. The storage equation modification is based on a soil moisture accounting procedure called the Antecedent Precipitation Index (API) which is designed to describe the soil moisture conditions over time during and after a storm event. In this method, the CN value is determined as a function of composite land use and soil drainage characteristics under AMC II conditions and fixed as a constant. The storativity is then defined in terms of the API such that:

$$S \rightarrow S^* = f(API) \tag{5}$$

where

S^* = a storativity time series,

API = Antecedent Precipitation Index = f(P(t)),

P(t) = precipitation time series.

The Antecedent Precipitation Index is designed to keep track of the soil moisture with time by the relationship:

$$API_n = APIK(API_{n-1}) + P_{n-1} \tag{6}$$

where

API_n = API on day n

API_{n-1} = API on previous day

APIK = coefficient representing the memory of the system, usually set at 0.9

P_n = precipitation on day n-1

The storage function is defined as:

$$S^* = S_{min} + (S_{max} - S_{min})e^{-SK(API)} \tag{7}$$

where

S_{min} = minimum value of S^*,

S_{max} = maximum value of S^*,

SK = a calibration parameter.

The maximum and minimum values for S are calculated from CN for AMC conditions I and III, respectively. Therefore, QUALHYMO allows S^* to vary with each time step between S_{min} and S_{max} for any CN as a function of API. SK then becomes the main calibration parameter in the SCS S^* procedure. SK is a parameter that is comprised of the physical and chemical properties of the soil, drainage efficiency, and other factors. Because it is an empirical parameter it requires relatively large data sets for its calibration, and, therefore, is arbitrarily assigned in the modeling procedure.

At the heart of the model's calculations is the SCS-CN method, which is tested herein.

STUDY AREA

General

The study area is located in the southwestern region of Nova Scotia in Eastern Canada in the Annapolis Valley. The boundaries of the watershed are defined by the surface topography and the direction of water flow into the Annapolis River and its tributaries. The study area extended from approximately between 64° 45' - 65° 10' W and 44° 40' - 45° 05' N, at the town of Lawrencetown. A sub-watershed (Wilmot) is 55805 ha. These are the watersheds considered in this article.

The Wilmot sub-watershed occupies an area of 55805 ha, with a total reach length of 31653 m.

Total impervious area is 3870 ha; the impervious fraction is 0.07. The Lawrencetown sub-watershed has an area of 47763 ha, total reach length of 19277 m, total area impermeable 4945 ha; and an impervious fraction of 0.10.

Land Cover and Land Use

The majority of land use in the watershed area consists of crop lands and orchards (Trescott, 1968). Farms occupy about 19 percent of Annapolis County (Trescott, 1968).

The natural vegetation of the area is forest composed of softwoods and mixed softwoods and hardwoods. The indigenous forest communities have been greatly modified by direct and indirect influences of man and, in the Valley, very little undisturbed forest remains. Forests cover 78 percent of Annapolis County (Trescott, 1968).

Hydrology

The watersheds are located in the Annapolis Valley, draining into the Annapolis River or various tributaries including Nictaux River, Black River, Fales River, Zeke's Brook, and South Branch Annapolis River. Flow in two of the tributaries is regulated by power companies - Nova Scotia Power Incorporated in the Nictaux River, and Berwick Electric Commission, in the South Branch Annapolis River.

Various control structures exist on the rivers including causeways, dams, water withdrawals, culverts and stream alterations, all of which complicate the modeling process.

Precipitation Data

Areal distribution of precipitation in the Valley is highly variable. The climatic station at Greenwood is located near the centre of the Valley part of the basin and is probably as representative of the climatic conditions in the Valley as a station can be. This station was the primary source of precipitation data used in the QUALHYMO model simulation.

MODEL CALIBRATION AND VERIFICATION

General

Model calibration is the process of changing parameter values to obtain simulated results that most closely reflect recorded values. Model verification involves checking the validity of the parameter values for a period not originally simulated. The general approach to calibration in this study was one of trial-and-error in which various values for each parameter were tried, their effects were noted, and appropriate changes were made to improve agreement between simulated and recorded values of flow.

The trial-and-error method of continual running and rerunning of the model and additional software was facilitated by the creation of various batch files and macros.

Calibration Procedure

The basic procedure in calibrating the model was one of selective parameter value manipulation and a comparison of simulated flow values against recorded flow values using both numerical and graphical methods. The numerical method consisted of comparing simulated and recorded flow volumes over the simulation periods. The graphical method used the system of pattern recognition of the display of the two (simulated and recorded) hydrographs based on shape. These two methods directed the subsequent parameter manipulation. For example, if the simulated flow was less than recorded, the value of the Initial Abstraction (Ia) parameter could be adjusted to a smaller value to increase the simulated runoff. Other parameters could also be manipulated.

Reasonable values of model parameters based on watershed characteristics were chosen where applicable as an initial set of values. The model was run, the result compared, and the appropriate parameters were changed to achieve a better fit. The model itself was designed with certain physical processes in mind to model, and does not include an algorithm for flow regulation effects. However, if information relating flow through the turbines to power generation can be determined, this difficulty may be surmountable. The final, best overall resultant fits were used in this report.

Simulation dates ran from May to October of each study year.

Verification Procedure

Simulation periods can be of any length. Typically, one month is simulated then calibrated. Another, usually the following, month is typically chosen and the model run with the same parameter values — this is the verification process, checking that the results of the first simulation period were accurate, and that the parameter values used in the second simulation period were consistent with the originally simulated month. However, rather than using this standard procedure for calibration and verification a different, but valid, method was used. By running the model continuously over a longer period of time (about 6 months — 184 data points/days), the effects of parameter change on later months can be assessed immediately, rather than requiring a separate simulation for verification. That is, by simulating over one month, and at the same time, applying those parameter values to successive months yields an essentially built in period of simulation and verification. For example, rather than running a simulation for the month of May, calibrating the parameter values, then using those values as input for the following month of June, the simulation was run for both months (as well as until the end of October), yielding simulation results for all months at the same time. By attempting to calibrate the parameter values over the longer simulation period, a verification of those values in other months was immediately obtained.

For illustrative purposes, Figure 1 shows the standard display for the Lawrencetown Watershed Simulation Year 1990.

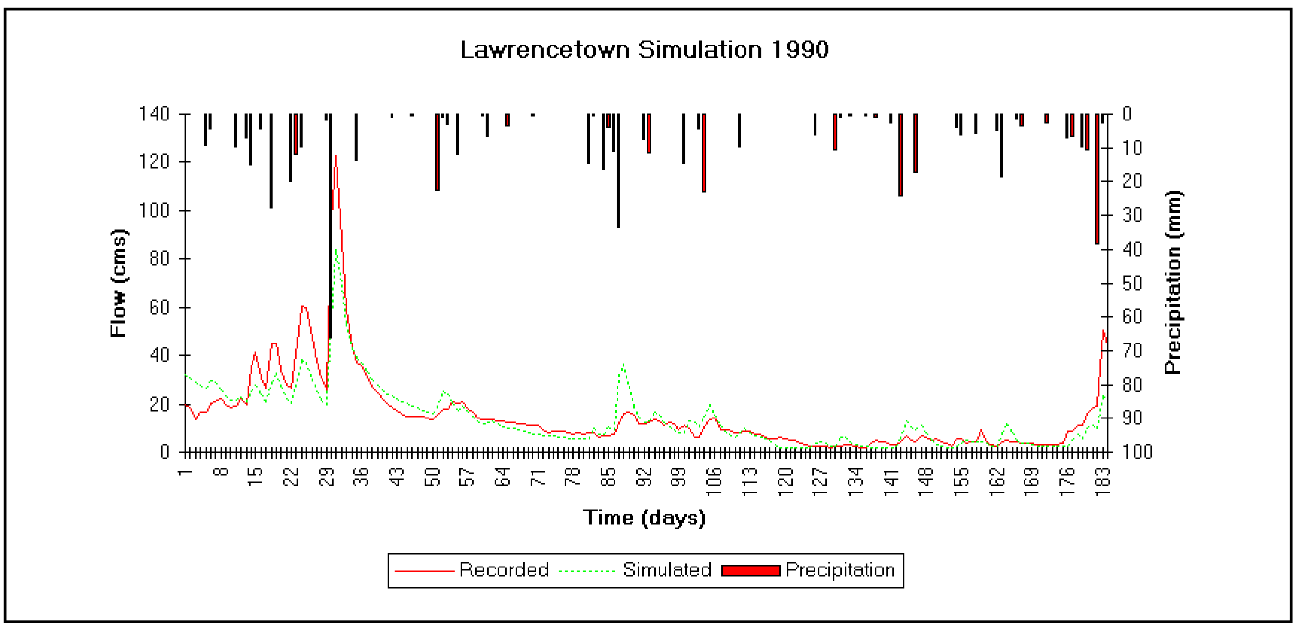

Figure 1. Simulated versus recorded flows for Lawrencetown: May 1 to October 31, 1990.

RESULTS

Error Calculation

Two numbers representing error were calculated for this report. One is simply a volumetric comparison of recorded versus simulated flow over a time period.

The other is a dimensionless number (R^2) representing the overall goodness of fit. In it, discharge at the outlet is considered the only variable upon which goodness of fit is established. The dimensionless approach gives less emphasis to peak values. It compares simply the actual and simulated flow values over the time frame and assigns a number, R^2, wherein the closer this value is to 1.00, the greater correlation there is between the simulated and actual flows. The equation for deriving R^2 is:

$$R^2 = 1/n\, [\Sigma_{i=1}{}^{n}(q_i - q)^2 - \Sigma_{i=1}{}^{n}(q_i - r_i)^2] \,/\, 1/n\, \Sigma_{i=1}{}^{n}\, (q_i - q)^2 \qquad (8)$$

where

$q = 1/n\ S_{i=1}{}^{n}\ q_i$

R^2 = analogous to the coefficient of determination

q_i = observed flow

r_i = simulated flow

n = number of values of record at evenly spaced time intervals

Calculations were performed in the spreadsheets containing the actual and final simulated flows using the built-in statistical functions of the Excel program.

Table 1 is a summary of a statistical analysis of the calibrated parameter values for the Wilmot watershed.

Table 1. Simulation Results for Wilmot Watershed

Year	**1989**	**1990**	**1991**
R	0.69	0.89	0.76
R^2	0.48	0.80	0.58
% Error	-8.32	-8.14	+2.03

Table 2 summarizes a statistical analysis for the Lawrencetown results.

Table 2. Simulation Results for Lawrencetown Watershed

Year	**1989**	**1990**	**1991**
R	0.52	0.90	0.77
R^2	0.27	0.81	0.60
% Error	-0.28	-6.79	-6.49

Sources of Error

Two basic sources of error are the precipitation and flow data as acquired from various sources. As these are the basic inputs to the simulation, errors in them can lead to large errors in simulation results as shown in Table 3.

Flow data comes from data collection stations located at the towns of Wilmot and Lawrencetown. Precipitation data is from the Greenwood Station, although data for the further Annapolis Royal Station allowed for a comparison of precipitation data impact.

The Annapolis Royal Station is located 32 km from the Wilmot Flow Station, while the Greenwood Station is only 8 km from the Wilmot flow station. A scattergram plot of precipitation between the two is shown in Figure 2, indicating the variation in precipitation throughout the Valley. The Wilmot Watershed has a length of 32 km, which is equivalent to the distance between the two precipitation stations and therefore is likely to experience the same degree of variability of precipitation over the distance, assuming a correspondence between the two distances. That is, given areal variation of precipitation over the Valley, the degree of variability within the watershed is potentially as great as the variation between stations.

The model was run for the Wilmot Watershed using the final calibrated parameter values using both the Greenwood and Annapolis Royal precipitation (ppt) data. By using the difference in average flow values for both simulations, and comparing them with the average flow value for the year, possible error can amount to 24 percent of total volume. There can be as much as a 24 percent average difference in resultant simulated flow using the two sources of data. This illustrates a potential variation in simulated flow using only one ppt station as input, due to the ppt variation over the watershed length. Lack of sufficient data representing ppt variation can result in a potential simulated flow volume difference of approximately 24 percent.

Flow data was collected by and acquired from Inland Waters Directorate (IWD). Stage readings are processed by IWD into a flow value based on stage-discharge curves, also generated by IWD. Numerous attempts were made to obtain the procedures IWD used to create their stage-discharge

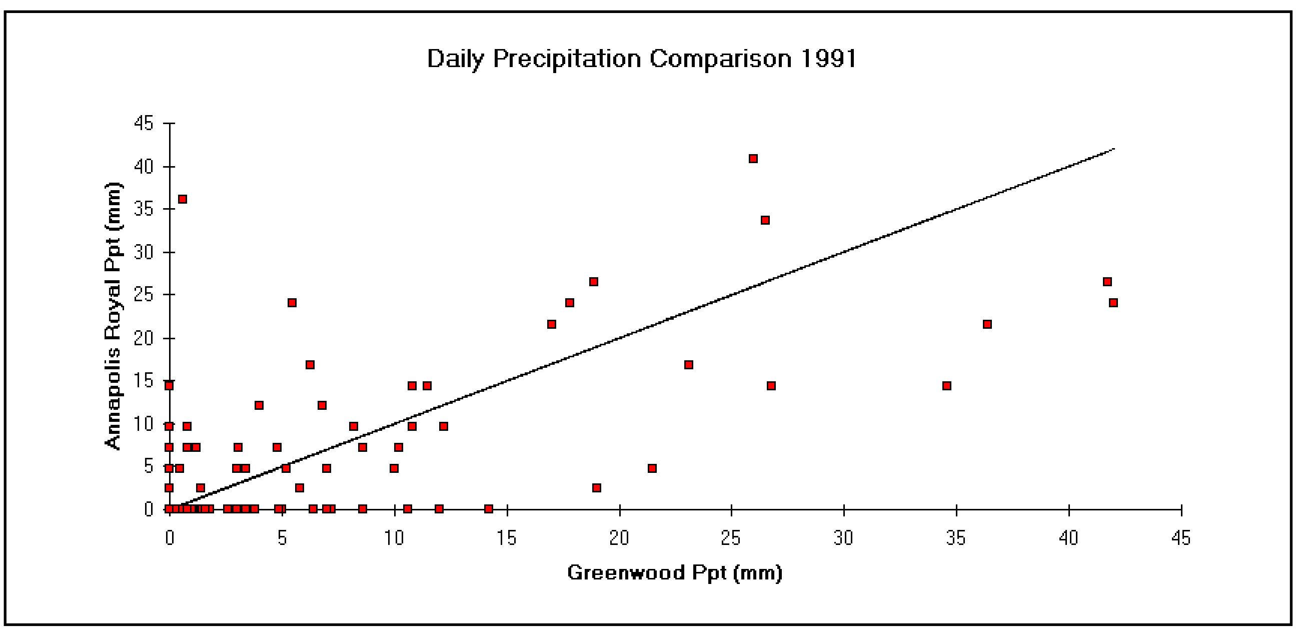

Figure 2. Scattergram of precipitation recording location.

relationships, but IWD was unable to provide them. Any errors in the stage value collection, the stage-discharge relationship, or the application of the stage-discharge curve can result in errors in the flow data.

Finally, the various possible sources of error that were inherent in the study include:

- the effects of flow regulation by the two Power Companies in the study area
- the effects of precipitation variability over the study area
- any inadequacies in the original data (precipitation and flow)
- the model not being properly calibrated for the existing watershed conditions

Table 3. Sources of Error and Effects on Simulation

Source of Error	Degree of Error (m^3/s)	Percent Error (%)
Precipitation Variation	2.6	24
Flow Regulation	3.8	36
Source Data	2.6	24

Given the potential effects on simulation, the degree of fit is acceptable. The error ranges from -8.32 percent to +2.03 percent (Table 2). Further parameter manipulation did not result in any improvement to the simulation.

A watershed that possesses sufficiently small areal variability of precipitation, no flow regulation from power generation or other activities, reliable flow data with no missing data would more fully meet the objective of this study. Future research should make use of more acceptable elements for simulation, as mentioned above.

CONCLUSIONS

The purpose of this paper was to determine the general applicability of the SCS procedure to large watersheds in excess of the original plot sizes and larger.

Some areas of concern are the low recorded flow peaks after large rainfall events that caused simulation challenges. However, this could have been due to several of the previously mentioned sources of error, or it could have been due to large river storage. Additionally, it may have been from the large size of the watersheds, and, because of this, the results of the study are technically inconclusive — the other sources of error would have to be eliminated before any conclusions of a definite nature could be attempted. Any future studies in this regard should select a better study watershed with less sources of error, that is:

1. The study watershed should have many precipitation data collection stations;
2. The study watershed should have reliable flow records as well as good stage-discharge relationships established; and
3. No flow regulation effects should exist in the watershed (power companies or otherwise).

However, given that the results are generally within 8 percent (simulated flow versus recorded flow), and, given the number of potential sources of error other than catchment size, these results would tend to indicate the apparent appropriateness of the model for use on these study watersheds, and, by extension, on large watersheds in general. Overall, the study would tend to indicate that size of watershed is not an impediment to application of the SCS method, but the rainfall distribution over the area could be of concern.

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