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MODELING URBAN RUNOFF FROM A PLANNED COMMUNITY

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Summary

A management strategy for utilization of water resources in the planned community of The Woodlands, near Houston, Texas, is being developed by modification and application of the EPA Storm Water Management Model (SWMM). Selected sites on Panther Branch, which flows through The Woodlands, and on Hunting Bayou, a completely developed watershed within the city limits of Houston, Texas were modeled for testing and verification of the modifications to the SWMM.

The capacity of the SWMM to model urban runoff quantity has been improved to include the "natural" drainage concepts of The Woodlands and the infiltration computation model in the SWMM is now capable of operating with a rainfall record which includes periods of zero rainfall. Three new subroutines have been written to operate in conjunction with the SWMM. The three subroutines generate normalized area-discharge curves for natural sections, model baseflow conditions, and model the operation of porous pavements, respectively. Verification of the SWMM with regard to suspended solids and BOD_5 was attempted and modifications to predict COD, Kjeldahl nitrogen, nitrates and phosphates were performed.

Scope of Study

Increased runoff rates and increased pollutant loads are two of the major effects of urbanization on the hydrologic regime of a previously undeveloped watershed. The increase in impermeable areas due to urbanization results in high velocity surface flows which tend to increase the potential for capture of pollutants by the storm water and reduce natural infiltration processes.

The planned new community of The Woodlands is designed to minimize the detrimental effects of urbanization upon the runoff characteristics of the watershed in which it is located. Several extensive changes to the U.S. Environmental Protection Agency Storm Water Management Model (SWMM) had to be performed to allow modeling of storm water runoff in The Woodlands by use of the SWMM. The necessary changes to the SWMM include modified computations for infiltration volumes and pollutographs and three new subroutines to develop normalized area-discharge curves for natural channel sections, to model baseflow conditions, and to model runoff from porous pavements. This paper discusses the changes that were performed to the SWMM, the new subroutines that were developed, and the concurrent modeling effort in The Woodlands. An urban Houston watershed, Hunting Bayou, was also modeled because its drainage characteristics are similar to those of The Woodlands.

The Woodlands Study Area

The Woodlands is a planned urban community being developed approximately 28 miles north of Houston, Texas in a heavily forested 17,800 acre tract in Montgomery County. A total of 33,000 dwelling units with a projected population of 112,000 is programmed at project completion in 1992. A concern for nature and convenience for people are two of the major criteria used in the development of the General Plan for The Woodlands, consequently, all development in The Woodlands is based on a comprehensive ecological inventory conducted from 1971 to 1973[1]. Approximately 33 percent of the total area, including all flood-prone land, is planned for open space uses. Some of the open space will be retained in its original state to provide wildlife habitat, while other areas will be maintained for park and similar recreational uses.

The Woodlands site is located in the Spring Creek Watershed. Panther Branch, an intermittent tributary to Spring Creek, is the major drainage channel as shown in Figure 1. Drainage channels tributary to Panther Branch and Spring Creek are characterized by broad and shallow swales having very mild slopes.

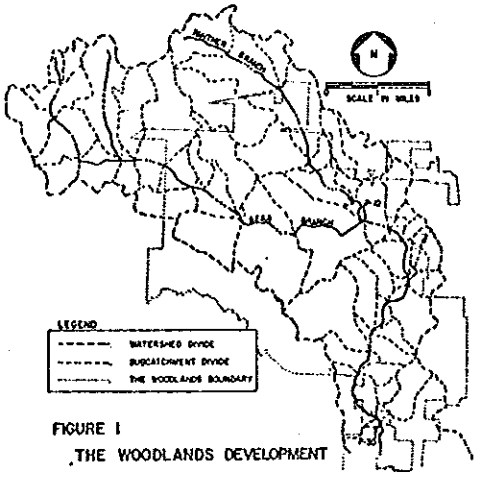


FIGURE 1
THE WOODLANDS DEVELOPMENT

A detailed soil survey by the U.S. Department of Agriculture Soil Conservation Service and the Texas Agricultural Experiment Station determined that the soils in The Woodlands site are highly leached, acid in reaction, sandy to loamy in texture and low in organic content. The vegetation is typical for a mixed woodlands of the Southern Piney Forest characterized by loblolly and short-leaf pines in association with hardwood species, including oak, sweet gum, hickory and magnolia[1]. The dense vegetation, sandy soils and mild slopes result in high retention and infiltration losses from rainfall.

The design of all drainage channels in The Woodlands is based on the premise that typically narrow and deep drainage ditches are undesirable. Therefore, the existing drainage channels are utilized to the fullest extent possible and any new channels are constructed as wide, shallow swales and lined with native vegetation to emulate the existing channels. Storm sewers and drains are used in high density and activity areas to conduct the excess runoff to the nearest drainage channel with sufficient capacity to safely carry the flow. To minimize increases in runoff volumes and peaks, retention ponds are utilized whenever practical.

The net effect of this "natural" drainage system is an increase in infiltration and storage capacity in the channels, thereby reducing the impact of urbanization upon the runoff regime.

Data Sampling and Sources

There are two stream stage recorders located on

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Panther Branch: Panther Branch near Conroe (P-10) and Panther Branch near Spring (P-30) as shown in Figure 1. Station P-10, located below the confluence of Panther and Bear Branches, measures runoff from 25.1 sq mi of undeveloped forest land. Station P-30 has a drainage area of 33.8 sq mi with the developing areas of The Woodlands (Phase I) immediately upstream.

The Hunting Bayou study area is located northeast of downtown Houston and within the metropolitan confines of the city. As seen in Figure 2, there are two gaging stations: Hunting Bayou at Cavalcade Street (H-10) and Hunting Bayou at Falls Street (H-20). The drainage areas of Stations H-10 and H-20 are 1.03 and 3.08 sq mi, respectively. Land use is primarily residential with some commercial and industrial areas. There are very few storm sewers and the major portion of the drainage system is made up of grass-lined swales comparable to those of The Woodlands.

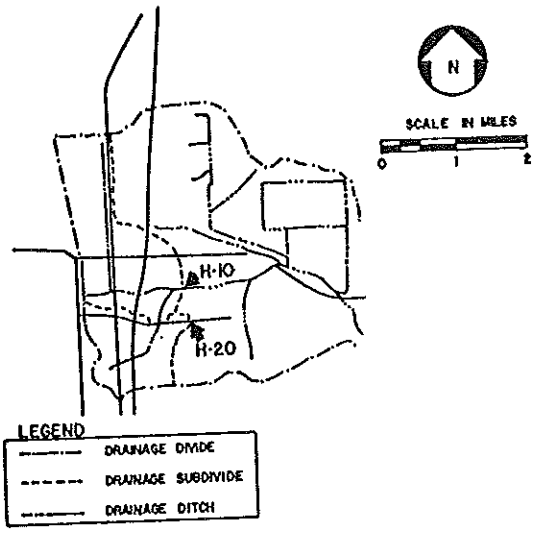


FIGURE 2--THE HUNTING BAYOU WATERSHED

During storm events, streamflow quality sampling was conducted in conjunction with flow gaging. The samples were analyzed for a large number of parameters including suspended solids, COD, nitrates, phosphates and Kjeldahl nitrogen. Reconstitution of the observed hydrographs and pollutographs to calibrate the SWMM were attempted in the modeling effort.

Modifications to the SWMM

The SWMM was originally developed to model the hydrologic effects of older urban areas where an artificial drainage system was imposed upon, and in most cases entirely replaced, the original drainage system. In the application of SWMM to The Woodlands, several deficiencies in the model were encountered. The major modifications are discussed in the following sections.

Modification to Infiltration Volume Computation

Infiltration rates are computed in the RUNOFF Block of the SWMM by means of Horton's Equation defined as follows:

$$f_c = (f_i - f_o)\, e^{-kt^*} + f_o$$

where:
- f_c infiltration rate at time t*
- f_i initial infiltration rate
- f_o final infiltration rate
- k decay coefficient
- t^* time from start of rainfall to the midpoint of the time interval Δt; or $t^* = t + 0.5\,\Delta t$

The RUNOFF Block of the SWMM was structured such that Horton's time dependant infiltration rate decay equation would become operative from the start of modeling time. Consequently, if the time of start of rainfall did not coincide with the start of modeling time, the infiltration rate would have decayed to a lower rate by the time rainfall had begun. This may be one reason why early investigators determined that the starting infiltration rate was not a significantly sensitive parameter[2]. A second problem with the computation of infiltration volume resulted from the input of two or more high intensity rainfall events separated by time periods of zero or low intensity rainfall that was not capable of satisfying the infiltration rate. The infiltration rate would decay without regard to the availability of rainfall for infiltration. Modeling runoff under these conditions was difficult and consequently the infiltration computation method in the SWMM was modified.

The new computation scheme uses an integral form of Horton's Equation and a time parameter to monitor the progress of infiltration only. The integral of Horton's Equation is:

$$M = f_o t + \frac{(f_i - f_o)}{k}\,(1 - e^{-kt})$$

where:
- M accumulated infiltration volume in inches at the end of time t

The other variables are as defined previously

During each time interval (Δt), the volume of water capable of infiltrating ($M_{t+\Delta t} - M_t$) is calculated and compared to the total volume of water available for infiltration determined as

$$D_t = S_t + R_t\,\Delta t$$

where:
- D_t water volume after rainfall during time interval Δt
- S_t water volume remaining from the previous Δt
- R_t intensity of rainfall during Δt

When the available volume is greater than the infiltration volume, the excess is calculated as the volume of water available for runoff. The results are comparable to those previously computed by the SWMM.

If the infiltration volume is greater than the available volume, the time increment, $\Delta t^* < \Delta t$, is computed such that the infiltration volume is equal to the available volume:

$$M_{t+\Delta t^*} - M_t = D_1$$

where:
- $M_{t+\Delta t^*}$ volume of infiltration at time $t+\Delta t^*$
- M_t volume of infiltration at time t
- D_1 volume of water available for infiltration

and no runoff is generated for that Δt.

The infiltration rate at time ($t + \Delta t^*$) then becomes the starting infiltration rate for the next computational time interval beginning at time ($t + \Delta t$). Therefore, the elapsed time for infiltration rate decay by Horton's Equation will not necessarily coincide with the elapsed runoff computation time.

Subroutine NATSEC

In the TRANSPORT Block of the SWMM, normalized area-discharge curves are required for flow routing. Thirteen uniform channel shapes (circular, rectangular, trapezoidal, etc.) have their respective curves preprogrammed through Block Data, but those for natural sections have to be independently computed and input to the model. Because of the large volume of work required in preparing these curves for a "natural" drainage system, Subroutine NATSEC was written and incorporated into the SWMM. This subroutine generates normalized area-discharge curves for irregularly shaped cross sections and for cross sections with varying values of Manning's roughness coefficient, n. The cross section is input to the subroutine by means of a two-dimensional linear coordinate system. Three Manning's n values, one for each overbank and one for the channel, may also be used. Depth increments for equal increments of area are calculated by an iterative process.

When the depth of flow is below bank elevations, a single application of Manning's equation is sufficient. If the channel capacity is exceeded, the flows in each overbank as well as flows in the channel are computed by independent applications of Manning's equation to each flow area. The total discharge is equated to the sum of the individual discharges.

The output from subroutine NATSEC is a tabular version of the normalized area-discharge curves for natural channels and is comparable to the other area-discharge curves in Block Data of the SWMM.

Subroutine BASFLO

The SWMM computational scheme considers all infiltration volume as permanently removed from the runoff volume. The volume of rainfall that soaks into vegetation debris and surface soils and which drains out at a very delayed rate is not accounted for because in most urban areas this interflow volume is negligible. But, again, in the "natural" drainage system of The Woodlands, interflow does become a significant factor. In vegetated areas, the volume of infiltration as computed in the SWMM includes evapotranspiration losses and losses to groundwater. Interception losses may be accounted for in either the infiltration or surface depression storage.

The portion of the hydrograph beyond the point of inflection (where $dQ/dt \to \infty$) is generally considered as depletion of runoff volume stored in the drainage system or watershed. As for most depletions in nature, the rate of depletion approximates an exponential decay and is often referred to as baseflow recessions[3] of the form:

$$Q_{t+\Delta t} = Q_t \, e^{-k\Delta t}$$

where: $Q_{t+\Delta t}$ flow at end of time interval Δt
Q_t flow at start of time interval Δt
k recession coefficient

The recession coefficients and their associated flow ranges are user-supplied to Subroutine BASFLO. One theory of varying recession coefficients for a single hydrograph is the concept of drainage of different storage units in the hydrologic system[4]. In The Woodlands, both stations P-10 and P-30 exhibit 2 recession ranges. The recession coefficients (determined from observed hydrographs) are plotted against the flow at start of recession and the corresponding regression equations are derived. The coefficients of the regression equations are input to Subroutine BASFLO. All flow rates beyond the point of inflection are determined by consecutive applications of the recession coefficient regression equations and the baseflow recession equations.

Subroutine BASFLO also provides for inclusion of the groundwater component of runoff. The groundwater flow rate may be input as a constant, linearly varying, or logarithmic function. All computed groundwater flow rates are added to the runoff hydrograph with respect to time resulting in a corresponding upward shift in the runoff hydrograph.

The baseflow rates are substituted into the runoff hydrograph prior to addition of groundwater flow rates. The specific water quality loading rates are applied to the new flow rates and the corresponding pollutographs are computed.

Subroutine PORPAV

The Woodlands Development Corporation has envisaged an extensive use of porous pavements in the place of conventional impermeable pavements. Subroutine PORPAV was developed to model the effects of porous pavements on the runoff volume and peak flows because the SWMM did not have this capability.

The modeling scheme consists of delineating the porous pavement and the subgrade as two hydraulically connected control volumes for which the inflow and outflow conditions are established by the equation for continuity or conservation of mass:

$$\frac{ds}{dt} = I - O$$

where: $\frac{ds}{dt}$ change in storage during time interval dt
I time average inflow
O time average outflow

Inflow to the porous pavement area is determined as the sum of direct rainfall onto the pavement and the overland flow hydrograph as computed by Izzard's method[5].

The outflow is the sum of vertical seepage losses, horizontal seepage losses, surface runoff when the porous pavement storage capacity is exceeded, and evaporation losses. Vertical seepage losses are computed by the variable head permeability equation. A modified Darcy Equation is used to model the horizontal seepage losses and Manning's Equation is used to establish the surface runoff rate. The instantaneous evaporation loss rate is computed from a time-lagged sine curve approximation of diurnal evaporation loss rates.

Unfortunately, no data on existing porous pavements are available. Therefore, all testing of Subroutine PORPAV has been done on a hypothetical area.

Storm Water Quality Modeling

A thorough analysis of the available water quality data from The Woodlands was conducted in an attempt to define a methodology to predict runoff quality, specifically nitrates, phosphates, Kjeldahl nitrogen, and

COD. The present version of the SWMM considers these as percentages of the dust and dirt volume. Recognizing that in The Woodlands the dust and dirt generation rates are not typical of other urban areas, relationships between quantity and quality of flow were sought. Plots of cumulative pounds of pollutant versus cumulative volume of flow indicate a strong relationship as shown in Figure 3.A for COD. In some cases, if availability of the pollutant is exceeded, the upper portion of the straight line will curve upwards indicating that the rate of pollutant loading is decreasing with increasing flow. Also, it was determined that total pollutant loading in units of pounds per acre is a function of total inches of runoff as shown in Figure 3.B for COD. The slopes of the straight lines tend to increase with urbanization, indicating an increase of pollutant loading for the same volume of runoff. The relative magnitude of the urbanization effects may be determined by the increase in slope.

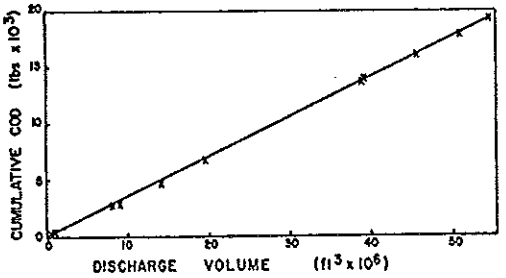


FIGURE 3.A--DOUBLE MASS ANALYSES FOR THE STORM OF 12/05/74 AT GAGE P-30

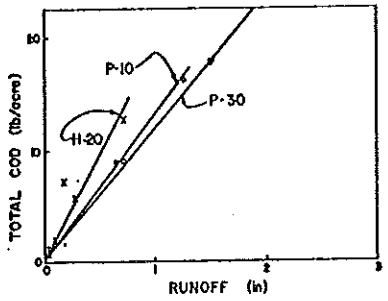


FIGURE 3.B--TOTAL POLLUTANT LOADING RATES

The pollutant loading relationship may be used to determine total pollutant mass and the cumulative pollutant mass relationship can provide a flow dependent mass transport rate. A combination of the two functions can be used to develop a pollutograph.

This methodology to determine quality of runoff is unrelated to the dust and dirt accumulation approach as used in the SWMM. Consequently, the quality of runoff computations in the SWMM would have to be completely rewritten to incorporate the new methodology. A simpler modification involves the input of user supplied pollutant loading rates. Initial modeling attempts using this approach are now being conducted.

Application of SWMM to The Woodlands and Hunting Bayou

The 33.8 sq mi of drainage area upstream of Station P-30 was divided into 57 subcatchments with an average size of 380 acres. Physical parameters were determined from topographic maps obtained from the U.S. Geological Survey and The Woodlands Development Corporation. Certain parameters such as width of subcatchment and retention depths cannot be directly determined for natural watersheds. Therefore, these parameters can be adjusted within reason so that a good fit exists between observed and computed hydrographs. Width of subcatchment values were first estimated using the method described in the SWMM User's Manual. These values had to be reduced by approximately 40 percent because overland flow will not occur as sheet flow over the entire subcatchment.

The parameters for infiltration modeling at Stations P-10 and P-30 are listed in Table 1. Table 2 lists the observed and computed peak flows and volumes and Figures 4 and 5 compare the observed and computed hydrographs and suspended solids pollutographs for the storm of 12/05/74 at Stations P-10 and P-30, respectively. The SWMM predicts suspended solids transport very well at the P-10 gage, but the prediction at the P-30 gage is not as successful. One reason may be the transient state of construction and development in the drainage area between the two gages. Accounting for all construction areas and their erodibility prior to the storm event being modeled proved to be difficult. Consequently, it is presumed that several construction areas where the natural ground had been disturbed and stripped of the protective vegetative cover contributed more suspended solids than the SWMM could predict from the available input data.

TABLE 1 -- INFILTRATION PARAMETERS FOR PANTHER BRANCH WATERSHED

STORM DATE	STATION	INFILTRATION RATES Initial in/hr	Final in/hr	Decay /sec
10/28/74	P-10	3.5	0.01	.0005
	P-30	3.5	0.01	.0005
11/10/74	P-10	0.3	0.01	.00115
	P-30	0.3	0.01	.00115
11/24/74	P-10	2.0	0.01	.00115
	P-30	2.0	0.01	.00115
12/05/74	P-10	0.5	0.01	.00115
	P-30	0.5	0.01	.00115
12/10/74	P-10	0.2	0.01	.00115
	P-30	0.2	0.01	.00115

TABLE 2 -- SUMMARY OF MODELING RESULTS FOR PANTHER BRANCH

STORM DATE	STATION	PEAK FLOW OBS. cfs	PEAK FLOW COMP. cfs	RUNOFF VOLUME OBS. 10^6cu.ft.	RUNOFF VOLUME COMP. 10^6cu.ft.
10/28/74	P-10	342	360	24.40	29.03
	P-30	376	410	39.34	36.16
11/10/74	P-10	979	600	64.48	53.44
	P-30	897	705	72.87	73.61
11/24/74	P-10	680	645	52.24	57.72
	P-30	774	735	73.70	78.97
12/05/74	P-10	273	315	36.06	32.66
	P-30	329	370	45.52	48.55
12/10/74	P-10	464	380	44.42	33.61
	P-30	517	425	51.73	43.02

The 3.42 sq mi of drainage area upstream of Station H-20 was divided into 24 subcatchments with an average size of 91 acres. Physical parameters were determined in a manner similar to that for Stations P-10 and P-30. The infiltration parameters and the observed and computed peak flows and volumes at Stations H-10 and H-20 are listed in Tables 3 and 4, respectively. The observed and computed hydrograph and suspended solids pollutograph for the storm of 5/08/74 at Station H-20 are shown in Figure 6. During the initial phases of the modeling program it was determined that due to testing difficulties, BOD_5 modeling could not be verified.

As seen in Figures 4, 5, and 6, the computed hydrographs are reasonably acceptable, but the suspended solids pollutographs for urban areas are severely deficient. Other investigators have arrived at a similar conclusion[6].

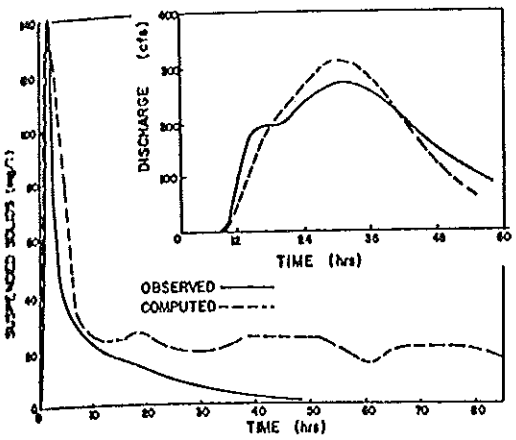


FIGURE 4--GAGE P-10, STORM OF 12/05/74

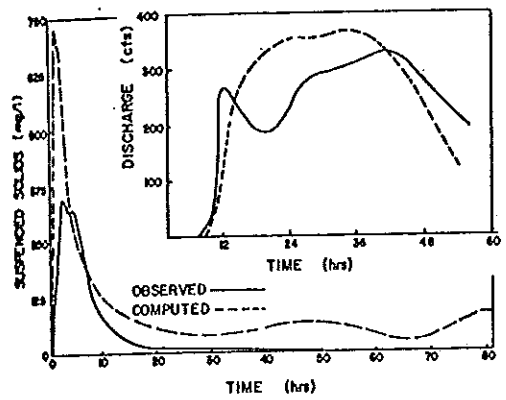


FIGURE 5--GAGE P-30, STORM OF 12/05/74

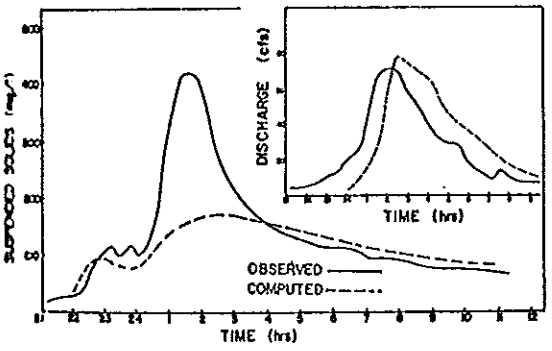


FIGURE 6--GAGE H-20, STORM OF 5/08/74

Future Directions

The modifications and additions to the SWMM which are discussed in this paper indicate that the modeling of storm water runoff quantity by the SWMM has been considerably improved. The new infiltration and baseflow models allow a closer parallel to the observed hydrograph.

The modeling of smaller subcatchment areas with more definitive hydrologic regimes will provide a method of evaluation of the capabilities of the new subroutines and computational methods in the SWMM. This type of data are presently being accumulated in The Woodlands.

Storm water quality modeling in the SWMM is constantly being improved but the results are still less than satisfactory as shown in the preceding section. The present size and structure of the SWMM limits the

TABLE 3 -- INFILTRATION PARAMETERS FOR HUNTING BAYOU WATERSHED

STORM DATE	STATION	INFILTRATION RATES Initial in/hr	Final in/hr	Decay /sec
9/08/68	H-10	1.00	0.10	.0005
	H-20	1.00	0.10	.0005
9/17/68	H-10	0.75	0.10	.0005
	H-20	0.75	0.10	.0005
11/09/70	H-10	2.50	0.10	.0005
	H-20	2.50	0.10	.0005
3/26/74	H-20	0.10	0.02	.0005
5/08/75	H-20	0.30	0.10	.0005

TABLE 4 -- SUMMARY OF MODELING RESULTS FOR HUNTING BAYOU

STORM DATE	STATION	PEAK FLOW OBS. cfs	PEAK FLOW COMP. cfs	RUNOFF VOLUME OBS. 10^6cu ft	RUNOFF VOLUME COMP. 10^6cu ft
9/08/68	H-10	121	160	1.43	1.85
	H-20	325	355	4.48	4.69
9/17/68	H-10	144	155	2.82	2.24
	H-20	333	365	8.37	6.02
11/09/70	H-10	85	125	1.50	0.97
	H-20	161	220	3.50	2.65
3/26/74	H-20	40	38	1.46	1.93
5/08/75	H-20	73	80	1.38	1.32

application of the new methodology described in this paper. Therefore, it is expected that any significant improvement in water quality modeling by the SWMM will necessitate a complete revision of the present methodology.

In conclusion, the SWMM has been a valuable tool in determining the storm water runoff characteristics of The Woodlands. The quantity of flow has been predicted satisfactorily and the quality of flow from undisturbed areas is also satisfactory. The modeling of quality of flow from disturbed areas is very complex and further detailed data and study are necessary.

Acknowledgements

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