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ON MODELS TO BE USED IN SWEDEN FOR DETAILED DESIGN AND ANALYSIS OF STORM DRAINAGE SYSTEMS

Anders Sjöberg[x)]

ABSTRACT

Computerized urban runoff models like ILLUDAS, NIVA, CTH and SWMM are sufficiently detailed and accurate to meet the requirements for proper design of storm sewer networks. The users, however, should be provided with guidelines concerning the schematization level with respect to runoff surfaces and pipe network and also concerning rainfall input data. Present design methods, represented by the Rational Method and the Retardation Diagram Method, have a limited utility.

INTRODUCTION

Present storm drainage design practice in Sweden is based on the Rational Method and Time-Area Methods. However, interest in practical use of the new computer simulation models of urban runoff as for example ILLUDAS (1) and the CTH-model (2) is increasing. This increasing interest was manifested by statements from practicing engineers participating in a recent course, Computer calculation of storm sewer networks, given by the Urban Geohydrology Research Group, Chalmers University of Technology, Gothenburg. The course was focused on practical application of a "Swedish version" of the ILLUDAS-model (3), which will be made available to external users at university computer centers.

Up till now, urban runoff simulation models have been used very little outside different university research groups. Many prac-

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tioners have reservations about the utility of computer models because they consider them too cumbersome and too expensive to use. The main reason is, however, that no user-courses have been given and that no computer programs have been readily accessible to external users. A lot of reports on simulation models have been published. However, a real interest and understanding of model structures and the capability of the models can obviously be gained only in courses which give the participants hands-on experience in running the models on a computer.

The university research groups have wide experience and insight in different urban runoff simulation models. Even if the researchers are not yet ready to solve or to give recommendations as to how to solve every possible problem, they have now reached such a level of knowledge and experience that more stress should be put on the question how to get the models into practical use.

The purpose of this paper is to present in Sweden presently accessbile simulation models and to introduce some thoughts about model improvements and future research activites. The discussion will be limited to models intended for detailed hydraulic design or analysis of storm sewer networks.

2 NEEDED MODEL CAPABILITIES - ACCESSIBLE MODELS

Urban runoff simulation models serve as an aid to decision making in problems of water quantity and quality caused by urban storm water and combined sewer runoff. Although the decision processes are oriented towards an overall solution, the problems and objectives attached may be subdivided into the following groups:

- Planning (preliminary large scale analysis of different storage-treatment combinations for given quantitiative and qualitative runoff criterias).
- Design/analysis (detailed design of gutters, inlets, pipes, detention basins, overflows, etc in new networks and analysis of the performance of existent networks).
- Operation (actual control decisions for in-system storage or diversions during a storm event).
- Optimization (technical-economical optimization of the system).

This division of the problem has limitations but it is convenient in that it agrees with the usual classification of simulation models. Each objective has produced models with somewhat different characteristics but the various models overlap on objectives to some degree. As mentioned above this study is limited only to models which can meet the objectives of detailed hydraulic design/ analysis. Simulation of pollutant runoff is not considered.

Table 1. Substructures in a local storm sewer system.

Substructure	Design depends on detailed hydrological hydraulic simulation of runoff
Street inlets	No (not presently)
Pipes	Yes
Junctions	No (not presently)
Overflow structures	Yes
Detention basins	Yes
Pumping stations	Yes

A local storm sewer system in Sweden normally contains the substructures given in Table 1. For the design of most of these substructures a complete description of flow routing from the point of rainfall through the entire urban runoff system is needed. The model should thus be capable of supplying the following informations:

- Flow hydrographs in all design points.
- Water levels along the sewer system (especially at surcharged conditions).

A list of models, able to supply the required information, could be made very long, see for example Colyer and Pethick (4). As we are here interested only in models which can be publicly disseminated, proprietary models have been excluded. Besides, only models which have gained some level of interest in Sweden are considered.

The capabilities of selected urban runoff models in this manner are listed in Tabel 2. The indications given are based on the ones presented by Huber, (19), but they are modified according to the authors opinion and experience.

Table 2. Capability of selected urban runoff models. Indications given refer to degree of sophistication.

Model	Surface routing	Sewer routing	Backwater surcharge	Detention basins	Overflow	Pumping	Design	Proprietary	Units	Reference
Rational Method	Peak flows	-						Free		(5,6)
Retardation Diagram Method	Low	Low					Yes	Free		(7)
NIVA (original)	Low	Moderate		Low	Low	Yes	Yes	Intended to be let free	Metric	(8)
NIVA[1)]	High	Moderate		Low	Low	Yes	Yes		Metric	(9)
ILLUDAS[2)] (Swedish version)	Moderate	Moderate		Low	Low		Yes	Free	Metric and amer.	(3)
CTH	High	Moderate		High			Yes	Free	Metric	(2)
SWMM:[3)]										(10)
Runoff block (RUNOFF)	High	Moderate		High				Free	Amer.	
Transport block (TRANS)		Mod. high		High	High	Yes		Free	Amer.	
WRE Transport block (EXTRAN)		High	Yes		High	Yes		Free	Amer.	

1) The SWMM Runoff block has been added to the original NIVA-model.

2) ILLUDAS is continuously modified and adapted to Swedish standards.

3) The SWMM (Storm Water Management Model) is developed under the sponsorship of the USA Environmental Protection Agency. SWMM is built up by the following blocks: RUNOFF (quantity and quality of surface runoff, routing in gutters or pipes, snow melt), TRANS (routing in main sewer system, backwater effects not considered), EXTRAN (routing in main sewer system, backwater and surcharging considered), STORAG/TREAT (effect of storage/treatment facilities), RECEV (receiving waters response). These blocks can be combined in different ways. The runoff block generates input data to TRANS and/or EXTRAN. For simple networks runoff hydrographs can be calculated by means of the RUNOFF block, only.

Almost any flow situation can be simulated at any desired level of sophistication by means of the models listed. The Rational Method can give a rough estimate of design peak runoffs rates. NIVA, ILLUDAS, CTH or SWMM (RUNOFF and TRANS) can be used to analyse the performance of an existing network for a particular storm event. In case of significant backwater effects or surcharged flow conditions we have to use the WRE transport block (EXTRAN) in SWMM to route the flow through the sewer system. The different models thus represent the three design/analysis levels defined in table 3.

Table 3. Design/analysis levels and corresponding models.

Design/analysis level	Needed information	Appropriate model
Rough estimate of design peak runoffs for small homogeneous areas	Peak flow	Rational Method
Detailed design/ analysis in case of insignificant backwater effects and no surcharging	Hydrographs	ILLUDAS NIVA CTH SWMM (RUNOFF) SWMM (TRANS)
Detailed analysis in case of significant backwater effects and surcharging	Hydrographs Waterlevels	SWMM (EXTRAN)

Models should be accessible (that means programs, documentation and advisers) in Sweden at each of the given levels. We do not yet, however, have experience enough to choose one specific model at each level or to choose one program-package covering all the objectives. The different models still have to be improved and modified paralel to each other and more experience from practical applications is needed.

SWMM seems to be the most complete simulation package available today. A serious drawback, however, is that the program is written for American units only. This limitation may prevent the use of the model outside university research groups in Sweden. To overcome this problem the program has to be converted to metric units (or SI-units) in the USA or the Swedish government should support the development of pre-processors and post-processors to meet Swedish conditions. Prof W James, McMaster University, Ontario, took a step in this direction. During his sabbatical year 77/78 in Sweden, he developed a pre-post-processor package called SWESWMM that makes it possible to run parts of the Runoff block of SWMM (snow melt, quality, plotting excluded) from a terminal in a conversational mode and with metric units (11). As the SWMM-package is continously improved and updated in USA internal coding must be avoided.

The only Swedish experience of the SWMM-package is so far limited to the SWESWMM-program. The total package is however under implementation at all the technical universities and it will presumably be available for use in various research projects.

3 ILLUDAS, NIVA, CTH AND SWMM

All these models simulate the different physical steps involved in the runoff process, figure 1.

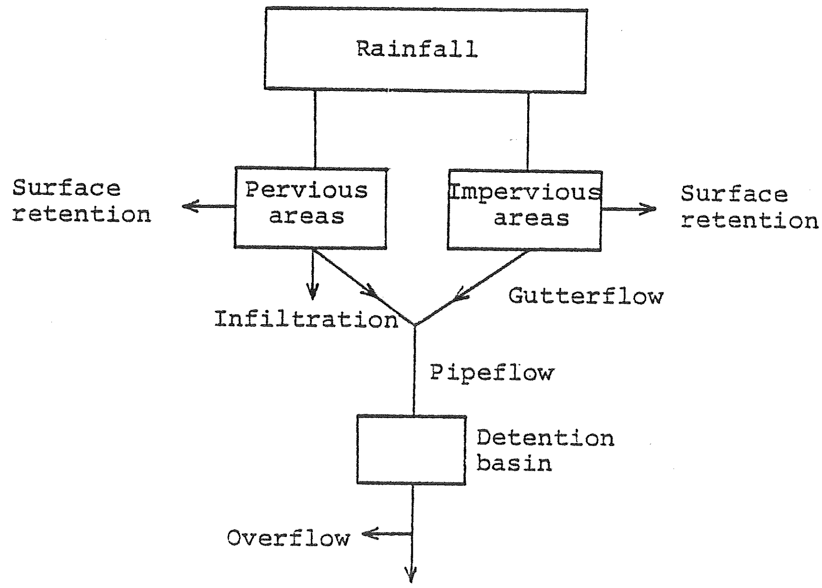

Figure 1. Structure of the runoff process.

The procedure differs from model to model but the differences are actually quite small, in so far as the impact on calcalated hydrographs is concerned.

As can be seen from table 4, the basic element of the models are the so-called NLR - and NLRC - routing routines (authors denomination). These routines are simple non-linear reservoir models, figure 2, but may also be interpreted as difference approxima-

Table 4. Model capabilites (see also table 2).

	ILLUDAS	NIVA (orig)	NIVA	CTH	SWMM RUNOFF	SWMM TRANS	SWMM EXTRAN
Impervious areas	Yes		Yes	Yes	Yes		
Pervious areas	Yes	Runoff coeff	Yes	Yes	Yes		
Surface retention	Yes		Yes	Yes	Yes		
Infiltration	Yes		Yes	Yes	Yes		
Surface routing	Time-area	Time-area	NLR[1)]	[2)]	NLR		
Gutter routing			NLR	-	NLR		
Pipe routing	NLRC[3)]	NLR	NLR	NLRC	NLR	MKW[4)]	[5)]
Detention basins	$Q>Q_s$[6)]	$Q>Q_s$	$Q>Q_s$	NLR	-	NLR	
Overflow	$Q>Q_s$[7)]	$Q>Q_s$	$Q>Q_s$	-	-	[8)]	[8)]

1) Non-Linear Reservoir-model (NLR) (authors denomination)
2) Kinematic wave approximation according to (12).
3) Non-Linear Reservoir Cascade-model (NLRC) (authors denomination).
4) Modified kinematic wave according to (13).
5) Backwater and surcharged flow conditions (10, 14).
6) All flow in excess of an outflow setting is stored (crued description of the calculation procedure).
7) All flow in excess of an overflow setting is diverted.
8) Discharge formulas.

tions of the kinematic wave equations leading to a "diffusing kinematic wave" (attenuated wave). The only difference between the two models is that the runoff area (or the pipe length) may be split up into several reservoirs in the cascade-model (NLRC). A correct simulation of the runoff hydrograph in long pipes often requires the use of the NLRC-model (15). To prevent misuse of the models the users must have som guidelines for the choice

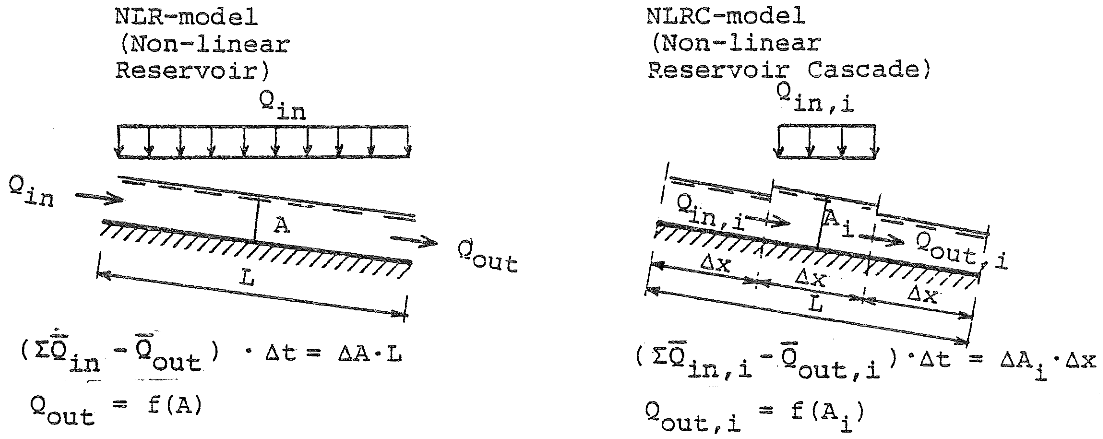

Figure 2. Relationships defining the NLR-model and the NLRC-model, respectively.

of $\Delta x/L$. The use of lengths in the calculations which are too long can lead to an artificial attenuation of the wave peak much greater than the real one.

The modified kinematic wave-routine, used in the SWMM Transport block, has been shown to be less sensible to the choice of pipe lengths than the NLR-model (15). The routine is however more expensive to use than is the NLR-routine and under certain conditions parasitic waves may disturb the solution.

For practical reasons it is impossible to give as input data all the physical properties necessary to describe every roof, parking place, local drainage pipes, etc. Thus the runoff area has to be simplified and schematized. The significance of the schematization level has to be studied and indicative guidelines have to be formulated.

In the author's opinion, all the models given i Table 4 are in the main sufficiently detailed and accurate to meet the requirements for detailed design and analysis of storm water networks in case of insignificant backwater effects. The following model improvements and additions to the users' manual area however recommended:

- Guidelines for choice of schematization level.

- Incorporation of the NLRC-routin + guidelines for the choice of $\Delta x/L$ (NIVA).
- Incorporation of the MKW-routine paralell to the NLRC-routine for routing in main sewers (research interest).
- Development of more realistic routines for detention basins and overflow structures (ILLUDAS, NIVA, CTH).
- Introduction of pumping-routines (ILLUDAS, CTH).
- Guidelines for the choice of rainfall input data.

Deterministic simulation models require a different type of precipitation data from that of the Rational Method. One can for example choose between using design rainfalls (developed from measured rainfall data) or time series of rainfalls (measured or statistically generated). Different approaches are currently studied in various projects (16).

The time-area method used in ILLUDAS for surface routing is judged as less sophisticated than the NLR-routine. This does not imply, however, that it is less useful and less powerfull from practical point of view. The correct use of the NLR-routine demands a detailed description of the runoff surfaces. Applied over a complex sub-area the NLR-routine is comparable to a lumped model and the geometric characteristics will be difficult to choose.

4 SURCHARGED FLOW CONDITIONS

For analysis of surcharging and backwater effects the WRE transport block EXTRAN in SWMM may be used. This routine was originally developed by Water Resources Engineers (WRE) (14), and later added to SWMM.

It is well known that routing models based on numerical solution (explicit or implicit difference schemes) of the full Saint-Venant equations give accurate representations of flows and water depths for free surface flow, provided suitable length steps and time steps are used. The same is true even for surcharged flow conditions as long as head losses in sewer junctions are unimportant. Head losses in manholes are, and probably rightly so, not considered a major factor when the sewers are not flowing full. Under surcharged conditions, however, the head losses may amount to several velocity heads (17, 18), and become important in judging the risk of flooding. Without the introduction of more realistic junction losses the EXTRAN block and other routines of the same type can not be considered to give more than rough approximations about pressure heads under surcharged flow conditions.

Another problem with "surcharge-models" is that the user may be faced with numerical instabilities, which cannot be readily removed by the user himself without the help of the developers. This is for example the case with the sewer network model DAGVL-A (15). Unfortunately the risk of instability seems to increase with the ability of the model to provide detailed simulation of different hydraulic conditions.

5 THE RATIONAL METHOD

The Rational Method, which can be traced back to the end of the 19th century, is the most widely used method for estimation of design peak runoff rates. By this method the peak runoff, Q, is found from

$$Q(T) = C \cdot MI(t_r, T) \cdot A$$

where T = the recurrence interval, in years

C = a dimensionless "runoff coefficient"

$MI(t_r,T)$ = a maximum average rate of rainfall intensity for a given duration, t_r, (in Swedish practice called "block-rain"). The intensity is obtained from intensity-duration-frequency (recurrence interval) relations

t_r = the duration of the block-rain, commonly equaled time of concentration or the travel time of water from the farthest point of the drainage area to the outlet. Independant of the actual runoff rate

A = the size of the drainage area.

The coefficient C is assumed constant and independent of t_r and T for a given area. Thus the calculated peak runoff rate is expected to occur with the same frequency as the rainfall intensity used in the computation. This assumption is basic in the Rational Method as it is used by storm drain designers. The so-called "runoff coefficient C" thus describes the relationship between the frequency distributions of peak runoff and block-rain intensity. This fact is not generally realized by designers, who often considers C to be just a runoff coefficient for calculation of the runoff part of the rainfall. The term "runoff coefficient" is misleading and technically imprecise. A more adequate term would be "peak runoff coefficient".

One of the major criticisms of the Rational Method arises out of the interpretation of C as a runoff coefficient and because such observed C-values for individual storms vary greatly during the storm and from storm to storm. As pointed out by Schaake et al (5) a method which would accomplish this variation would have to involve antecedent conditions and other variables of both the drainage area and the storm pattern. The Rational Method should not be used to estimate peak runoff rates or total runoff hydrographs for particular storms, nor can the value of C be estimated from individual rainfalls. C can be determined only from a statistical analysis of measured peak runoff rates and rainfall intensities. In fact, the Rational Method should be used only for calculation of design peak runoff rates.

The validity of the Rational Method for a 0.15 km^2 large urban catchment with about 40% impervious areas has been studied by Lyngfelt (6). Figure 3 shows the statistical distributions of maximum average intensities for different durations, t_r, and of measured peak runoff rates calculated from a two year historical record. The figure shows the strong dependence of the value C on the used duration, t_r. The difficulty in choosing these parameters leads to considerable uncertainty concerning the frequency of the calculated peak runoff rates. An estimation of C following usual design procedures in Sweden led to the value C = 0.44. This value in combination with t_r = 10 minutes (standard value for small areas) gives a 2 year peak runoff which is about 10% below the value according to figure 3.

The tendency for the rainfall and runoff distributions to converge has also been noted by Schaake et al (5). This fact implies that C increases with increasing recurrence intervals, i.e. with the more intense, less frequent intensities. The basic assumption, that a constant value of C gives the same frequency of occurence of the computed design peak runoff rate and of the used rainfall intensity, is however approximately satisfied.

The Rational Method is a method based on purely statistical arguments, and it may be used for estimates of design peak runoff rates for small, homogeneous and smoothly shaped urban areas. The values of C and t_r are however difficult to estimate. More information of the type presented by Lyngfelt (6) is needed and can be obtained from data collected in different urban areas.

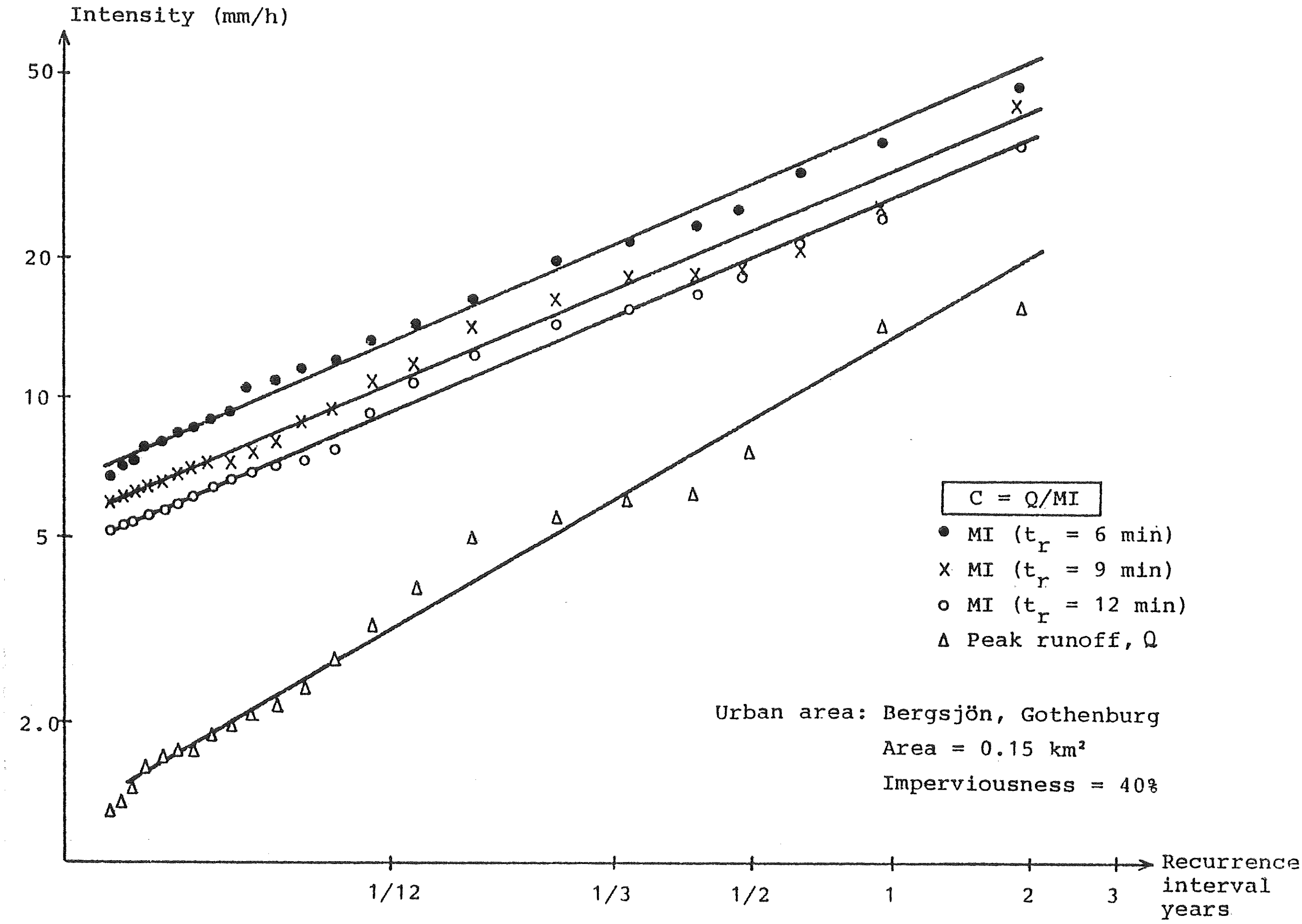

Figure 3. Statistical distribution of maximum average rainfall intensities MI for different durations t_r and that of measured peak runoff rates. From Lyngfelt (6).

6 THE RETARDATION DIAGRAM METHOD

Probably the most widely used method in Sweden for design of urban storm water systems is the so-called Retardation Diagram Method (7), also named the Summation Curve Method or the Outfall Diagram Method (direct translations from Swedish). The method is in fact a time-area method modified to suit design purposes and suitable for graphic solution if block-rain and time-independent runoff coefficients are used. Many consultants, however, have developed equivalent computer programs.

The sewered area is divided into sub-areas which are assigned appropriate times of entry and runoff coefficients φ. For a linear time-area relationship, the sub-hydrograph from each sub-area can then be calculated. The sub-hydrographs are routed through the sewers at some chosen routing speed, for example the flow velocity corresponding to the actual peak discharge and water depth in the pipe.

The Retardation Method is unfortunately considered as developed out of the Rational Method, which leads to much confusion in the discussions concerning these two methods. The Rational Method is, as pointed out above, based on purely statistical arguments while the Retardation Diagram Method at least partly simulates the physics of the runoff process. The latter model is thus a deterministic simulation model of the same type as the NIVA-model or ILLUDAS. It is however a very poor simulation model as it includes only the impervious areas (modeled by the runoff coefficient φ) and as it neglects pervious areas, surface retention and infiltration. Besides, the routing routine gives too slow a wave speed (15) and it does not simulate the attenuation of the wave peak. Attempts to improve this model will lead to models of the same type as the models discussed in chapter 3.

The Retardation Diagram Method can be used for rough graphical estimates of design peaks. However, one of the new simulation models should be applied instead of using computerized versions of the method.

7 CONCLUSIONS

In the authors opinion simulation models of the type ILLUDAS, NIVA, CTH and SWMM are sufficiently detailed and accurate to meet the requirements for detailed design and analysis of storm water networks in case of insignificant backwater effects. The users should be provided with certain model improvements and guidelines concerning

- The significance of the schematization level with respect to the runoff surfaces and the pipe network.
- The choice of rainfall input data for design purposes.

In case of surcharged flow conditions head losses in junctions may become important. Models like the EXTRAN block in SWMM should be furnished with more realistic values for junction losses.

The Rational Method, which is a method based on statistical arguments, may be used for estimations of design peak runoff rates for small, homogeneous and regularly shaped urban areas. More information is however needed concerning the choice of block-rain durations and corresponding peak runoff coefficients.

The Retardation Diagram Method is a very rough deterministic simulation model which includes only the impervious areas and neglects surface retention and infiltration. It should be replaced by one of the more powerful simulation models.

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