Wat. Sci. Tech. Vol. 27, No. 5-6, pp. 133–143, 1993.
Printed in Great Britain. All rights reserved.

0273–1223/93 $24·00

DYNAMIC DESIGN OF SEWER DETENTION TANKS

H. van Luijtelaar and P. P. G. Ganzevles

Grontmij nv, Consulting Engineers, P.O. Box 203, 3730 AE De Bilt, The Netherlands

ABSTRACT

In the Netherlands new regulations regarding combined sewer overflows have been proposed to reduce the pollution of surface water. These regulations will lead to the construction of ancillary sewer facilities. The current design methods are not suitable for optimizing measures to control overflow loads. Therefore a new method, called 'Dynamic Design', is proposed. This design method is based upon the use of time series of rainfall and advanced computer programs. By using longterm continuous simulation in combination with historical time series of rainfall overflow volumes, discharge durations and frequencies can be derived. These results can be analysed statistically to obtain frequency distributions of overflow volumes and discharge flows. This procedure ensures not only the assessment of detention tanks but also the evaluation of alternative measures like real time control and flow routing strategies. Dynamic design aims at the efficient use of ancillary sewer facilities to minimise receiving water impact. Several cases are discussed to show the advantages of dynamic design in comparison with current design procedures.

KEYWORDS

Dutch sewer systems, sewer detention tanks, combined sewer overflows, sewer modelling, time series of rainfall, longterm continuous simulation.

INTRODUCTION

Sewers in the Netherlands. The Netherlands are a flat country. As a result the gradient in most Dutch sewers is kept to a minimum. The diameters of the pipes used are large to ensure transport of storm water. Due to these characteristics Dutch sewers have a large storage capacity and several weirs, usually on the same level, to prevent flooding. Most of the sewer systems are combined systems. Traditionally the storage capacity of sewers has been assessed with a theoretical frequency of overflow. This evaluation is not sufficient with respect to receiving water impact. A national research program, supervised by the National Working Group on Sewerage and Water Quality (NWRW,1991), has been executed to obtain a better understanding of the discharge loads of sewer systems. The results of this research program are being used to improve regulations.

In the near future new, stricter regulations concerning the storm water discharge of combined sewer systems will be proposed in the Netherlands. A Dutch committee (CUWVO), responsible for the implementation of the Law on the Pollution of Surface Waters (WVO), has made a proposal to achieve 'a basic effort' as a minimum reduction of pollution (CUWVO, 1992).

This 'basic effort' will lead to the construction of ancillary sewer facilities, such as detention tanks. In the Netherlands the city councils are legally obliged to meet the new standards as they are responsible for the collection of sewage. The construction of extra storage capacity is estimated to require an investment of at least 2 billion Dutch guilders.

The general expectation is that most of the ancillary sewer facilities will be constructed as detention tanks. The traditional design method for such tanks is not suitable to justify substantial investments. Therefore this paper presents a new method, called 'Dynamic Design of Sewer Detention Tanks'. The application of this design method is based upon the use of the computer program NIVO/GM, developed by Grontmij nv, consulting engineers. This computer program simulates overflow discharges using continuous time series of rainfall.

Several case studies will be discussed to show the possibilities of the dynamic design method. This design method is not only restricted to the design of detention tanks. Therefore some examples of alternative solutions, such as additional pumping capacity and facilities with relatively large storage capacity, will also be discussed. Designing with NIVO/GM aims at the efficient use of required facilities to reduce the discharge of pollutants per overflow location.

TRADITIONAL DESIGN

The traditional design method for sewer detention tanks is based upon the following assumptions:

- the catchment area per weir of a sewer system is constant during a storm;
- steady flow calculations with a constant rainfall intensity (60 l/(s·ha)) predict the division of catchment area per weir;
- the design flow of a detention tank is equal to the multiplication of the derived division of catchment area and a constant runoff intensity (20 l/(s·ha)).

Division of constant catchment area. The assumption that the catchment area per weir is constant is only valid for sewer systems with one weir. In case of sewer systems with several weirs the division of constant catchment area per weir is made with a steady flow calculation. Only one rainfall intensity (60 l/(s·ha)) is used. In actual fact the catchment area per weir can vary considerably during a storm. This phenomenon is especially noticeable in systems in which the storage capacity is optimised by damming the storm water flow or in which weir levels have been adjusted.

Design flow of detention tanks. It is assumed that the design flow of detention tanks can be calculated by multiplication of the constant catchment area per weir and a constant runoff intensity (e.g. 20 l/(s·ha)). This approach disregards the actual overflow volumes and flows. The surface load of sewer detention tanks will be far from constant in contrast with the settlement facilities of sewage treatment plants.

The traditional approach is not suitable for assessing if a designed detention tank will work properly in a given place. Above all, the basic principles of this approach disqualify the evaluation of alternative measures to control overflow loads. The alternative measures -which will also be discussed in cases in this paper- are for example:

- the adjusting of the crest levels of weirs
- the introduction of real time control with additional pumping capacity
- ancillary structures with relatively large storage capacity.

The design of these alternative measures and detention tanks depends, amongst other things, on the available rainfall data. More detailed information regarding the course of rainfall is necessary. In this case time series of rainfall will give more insight. Dynamic models use the course of rainfall to simulate the functioning of sewer systems and ancillary structures, such as detention tanks, during a longterm period. This approach is no longer restricted to just some rainfall intensities but takes into account the rainfall data spanning several years.

DYNAMIC DESIGN

The dynamic design of sewer detention tanks is based upon the computer models NIVO/GM and EXTRAN/GM

EXTRAN/GM. EXTRAN/GM is the Grontmij version of EXTRAN (=EXTended TRANsport) derived from the EPA's Storm Water Management Model (Huber et al.,1984). EXTRAN is a hydraulic flow routing model for open channel and/or closed conduit systems. The model performs dynamic routing of storm water flows. A normative runoff hydrograph has been derived (Luijtelaar et al.,1990) for the assessment of flow capacity of sewer systems. The model EXTRAN/GM offers the possibility of simulation with large sewer systems. Unlike the traditional approach, dynamic design emphasizes the use of several runoff hydrographs to obtain detailed information about the way a sewer system responds to these storms.

NIVO/GM. NIVO/GM has been developed to simulate combined sewer overflows over a longterm period with a schematised sewer model. The continuous simulation with time series of rainfall enables the assessment of the storage capacity of a sewer system. The properties of the schematised sewer model are derived from the results of the EXTRAN/GM calculations with different runoff hydrographs. Figure 1 illustrates the relations between EXTRAN/GM and NIVO/GM.

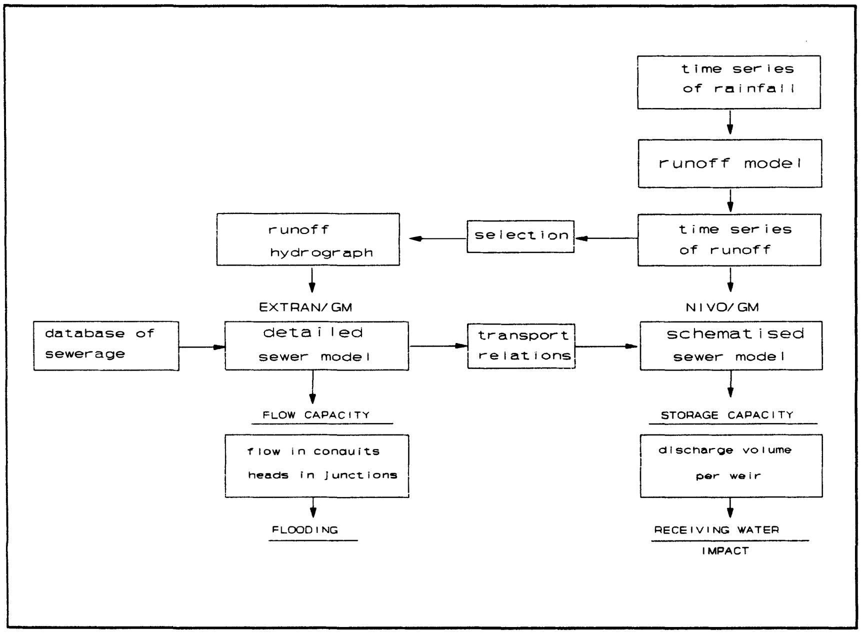


Figure 1. Diagram of relations between EXTRAN/GM and NIVO/GM

The use of time series of rainfall requires a schematisation of the detailed sewer model in order to restrict runtime of the continuous simulations. The schematised sewer model in NIVO/GM consists of a system of reservoirs and 'transport relations'. These transport relations represent hydraulic features like weirs and pumps. The schematisation is based upon the results of EXTRAN/GM calculations with different runoff hydrographs. This approach enables the calibration of the derived schematisation with the same hydrographs. This verification is repeated until the results of both EXTRAN/GM and NIVO/GM are sufficiently matching. Figure 2 shows the possibilities of NIVO/GM to approach the calculated discharge flow of EXTRAN/GM. In this case the runtime of hours with the detailed sewer model was reduced to seconds with the schematised one.

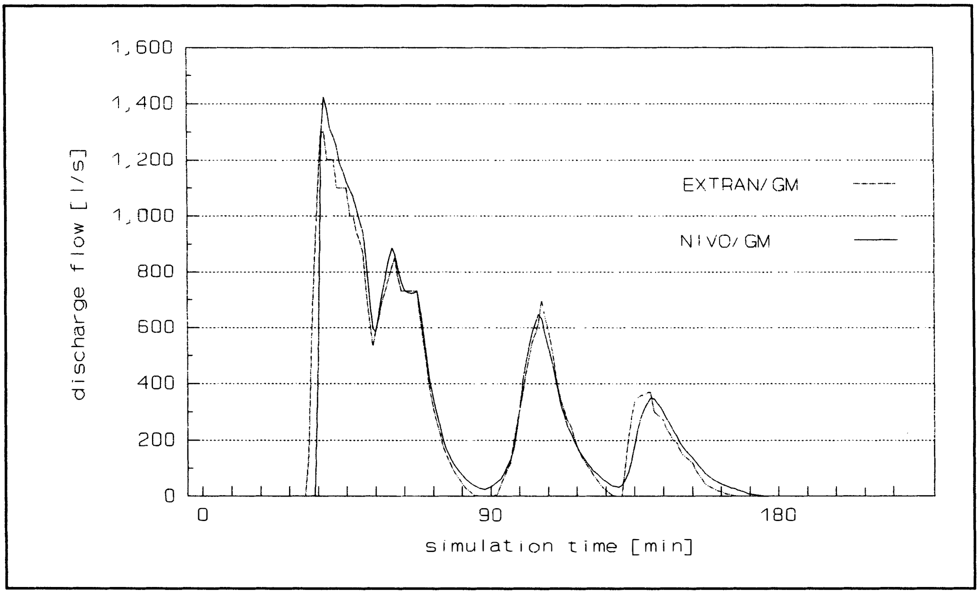


Figure 2. *Comparison of EXTRAN/GM and NIVO/GM for a same storm event*

Important information is obtained by the procedure in order to execute more detailed calculations with different kinds of storm events. This information concerns for instance the functioning of weirs during less severe storms and the probability of flooding during severe storms. The occurring flow velocities, which determine the transport of pollutants, during the different storms are also considered.

The schematised NIVO/GM sewer model enables the continuous simulation with time series of rainfall within an acceptable runtime. Three time series of rainfall can be used. These time series contain the rainfall data of 'De Bilt', 'Beek' and 'Eelde'. The rainfall data of these localities have been collected by the Royal Dutch Meteorological Institute during a period of 25 years from 1955 to 1979. The series are digitised with a time step of 15 minutes (Buishand et al.,1991). During simulations with NIVO/GM the overflow volumes per 5 minutes are recorded per weir. These results can be analysed statistically. Not only extreme and average discharge volumes can be derived but also the frequency distributions of discharge volumes and flows can be obtained. The pollutant loads per location are calculated in accordance with the findings of the NWRW research program by attaching the occurring flows to a recommended concentration of pollutants.
Other results of simulations with NIVO/GM are the durations of pumping and the retention time of sewage in tanks. This is especially of interest regarding the effectiveness of ancillary sewer structures with relatively large storage capacity and the efficiency of treatment plants.

Design procedure

The dynamic design of sewer detention tanks has a staged approach to achieve the optimisation of measures to control receiving water impact. Firstly the existing situation of a sewer system is analysed. The results of this analysis are meant to be a reference for the impact of possible measures. These measures will have to meet the standards of the 'basic effort'. This effort implies the reduction of pollution in accordance with the discharge of a reference sewer system with 7 mm storage capacity, 0.7 mm/h pumping capacity and 2 mm extra storage in detention tanks. Water boards may demand an additional reduction of pollution.

Subsequently possible measures are investigated. This preliminary investigation will have to determine suitable locations for detention tanks, the possibility for increasing pumping capacities, the characteristics of receiving waters and bottlenecks within the sewer system. Calculations with EXTRAN/GM are executed to assess the most appropriate measures.

Finally the effectiveness of alternative measures is compared through calculations with EXTRAN/GM as well as NIVO/GM. Additional EXTRAN/GM calculations and a NIVO/GM schematisation have to be made, if the characteristics of the sewer system are drastically altered by varying weir levels or increasing storage.

The schematised sewer model in NIVO/GM can be extended with additional storage of ancillary structures, such as detention tanks. The introduction of real time control is also possible. These program features enable the varying of design parameters so that the dimensions of sewer detention tanks can be adjusted to the specific discharge characteristics of a given weir. Eventually the results of the alternative measures are related to the existing situation and the assumed design criteria.

Design application

The use of historical time series of rainfall has clear advantages. The time dependent properties of storm, such as duration, intensity, the sequence and the variability due to seasons are considered. These characteristics are unambiguously registered and don't depend on a given storm definition.

The application of time series of rainfall discriminates dynamic design from traditional approaches, because more attention can be paid to the division of discharge volumes per overflow. This enables the dynamic design to meet regulations that consider the characteristics of receiving water.

Results of dynamic design can be related to actual measurements, for instance overflow frequencies. However, the quality of input data is decisive for the interpretation of measurements. Hence the use of runoff modelling (NWRW 4.3, 1989) to determine the amount of runoff demands not only the size of catchment area but also the division and type of catchment area (type of pavement, roofs, vegetation).

The basic principles of dynamic design offer possibilities that are not available with the traditional design methods. Some possibilities have already been announced:

- flow routing strategy through adjusting weir levels
- real time control with additional pumping capacity
- relatively large storage capacity in ancillary structures.

The possibilities of dynamic design are discussed in four cases. Case I presents the impact of flow routing strategy by adjusting the weir levels. The differences between the traditional and dynamic design of a sewer detention tank will be discussed in case II. The application of real time control with additional pumping capacity is put forward in case III. Finally case IV will show the use of ancillary structures with a large storage capacity. As example a rush field will be discussed.

CASES

Case I Flow routing strategy by adjusting weir levels

The receiving water impact is determined by the size of surface waters and the occuring flow regime. The effects are especially more pronounced in small ditches. Therefore flow routing strategy aims on one hand to let discharges take place on locations where surface water is less vulnerable and on the other hand to influence the location of detention tanks. In this case a very effective measure is to adjust weir levels or to remove weirs. Adaptations of the sewer system may be necessary to divert storm water to suitable overflow locations, where the surface water is less vulnerable and/or to detention tanks.

The variation of weir levels results in variation of the catchment area per weir due to the kind (storm. This means that the traditional approach cannot predict the division of catchment area per weir. Because of this a design flow cannot be determined for the design of a detention tank.

The flow routing strategy is applied to a sewer system with two weirs (A and B). Weir A discharges into vulnerable surface water. Weir B discharges into large and less vulnerable surface water. Therefore the weir level of weir A has been elevated by 0.50 m. The characteristics of the sewer system are:

- catchment area: 7.81 ha
- storage capacity: 8.1 mm
- pumping capacity: 0.7 mm/h.

The relative catchment area per weir determined with both the traditional and the dynamic approach is shown in table 1. The traditional design method relates the catchment area per weir to the division of discharge flows derived with one constant rainfall intensity of 60 l/(s·ha). The catchment area according to the dynamic approach is related to the discharge volumes spanning a period of 25 years (De Bilt 1955-1979).

Table 1. Division of catchment area per weir

weir	division of catchment area	
	traditional (60 l/s·ha)	dynamic (1955-1979)
A	18%	7%
B	82%	93%

Table 2. Division of discharge volumes (1955-1979)

weir	division of discharge volumes	
	same level	different levels
A	46%	7%
B	54%	93%

Table 1 shows that there is a significant difference between the division of catchment area according to the two design principles. For weir A the extrapolation of the traditionally derived division will lead to discharge volumes that exceed the dynamically derived division by a factor of 2.5. This difference can be explained. Weir A does not discharge during storms of less intensity. In this case most of the storm water is discharged by weir B. The traditional approach could derive catchment area per weir with storms of less intensity, but it is impossible to estimate the distribution of intensities.

In contrast to the traditional approach, the dynamic approach with NIVO/GM gives a more realistic insight into the division of discharge volumes per weir. In table 2 the dynamically derived division of overflow volumes is also shown for the situation that the weir levels are the same.

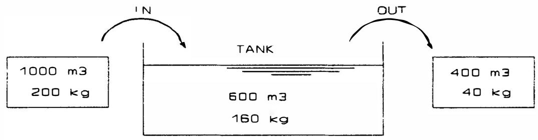
Table 2 shows that the elevation of the weir level is very effective. The overflow volume of weir A has been reduced to 15% of the original discharge volume. If a detention tank with 2 mm additional storage would have been installed downstreams of weir A, the overflow volume would have been reduced to 35% of the original discharge volume.

Case II Design of a sewer detention tank

A sewer detention tank works mainly in two ways. Firstly the size of the tank reduces the discharge volume. Secondly it is designed to retain suspended sediments by settling. So the total efficiency of a detention tank depends on storage and settling (the different efficiencies are defined in the example 'derivation of efficiencies').

Derivation of efficiencies

The following example is used for the derivation of efficiencies:



The efficiency of storage relates the reduction of pollution to the storage of incoming storm water. In this case the storage efficiency is equal to 60%; 600 m^3 of the incoming 1000 m^3 has been stored in the tank. The settling efficiency can be defined in two ways.

Definition 1 *This definition considers the potential sediment retention efficiency of a tank. This is related to the difference that will arise between the concentration of pollutants of incoming and outgoing storm water. The concentration of pollutants is reduced by a factor of 2 (incoming 0.2 kg/m^3 is reduced to outgoing 0.1 kg/m^3). This leads to an efficiency of 50%.*

Definition 2 *This approach relates the contribution of settling to the total reduction of discharged pollutant loads. The total reduction is equal to 160 kg, that is 80% of the incoming pollutant loads. The storage efficiency is equal to 60%. So in this case the settling efficiency is equal to 20%. A load of 40 kg is retained by settling due to the retention efficiency of 50% (definition 1) and the total discharge volume of 400 m^3.*

If the storage in a tank is increased, the contribution of settling decreases. This is shown in figure 3, in which the total efficiencies are related to additional storage in a tank. The total efficiency is divided in efficiency of storage and settling (definition 2). The suspended sediment retention efficiency (definition 1) is assumed to be 50%.

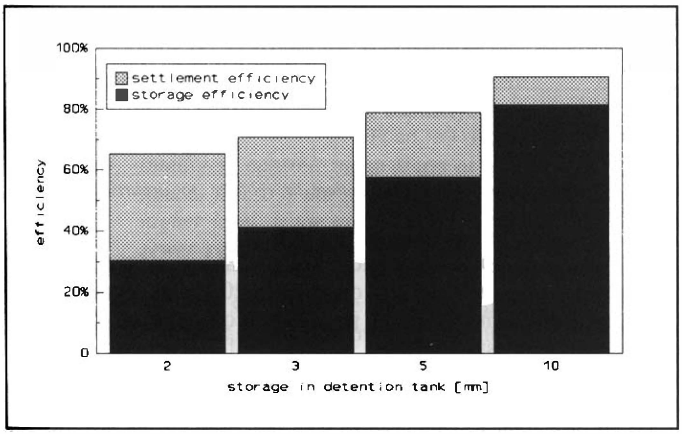


Figure 3. *Total efficiency of a detention tank in relation to its storage*

The division of storage and settling efficiency in figure 3 shows that the contribution of settling is most important for 2 mm and 3 mm additional storage. Therefore a further investigation of settling processes is relevant.

The settling of sediments in a detention tank depends on:

- physical characteristics of sediments, such as particle size and settling velocity
- the occurring discharge flows of the tank itself
- the geometric configuration.

The average settling velocity of suspended sediments determines the surface load of a tank. In most cases a surface load of 5 m/h is assumed. Traditionally these assumptions and a design flow lead to a geometric configuration of a detention tank. A simple variation of parameters is used to estimate the sensitivity to different flows and settling velocities of sediments in the tank. This assessment is not complete because the efficiencies of storage and settling cannot be derived due to the lack of the knowledge of the occurring discharge flows and volumes.

The dynamic approach gives more insight into the variation of discharge flows and volumes. As an example both the duration of flows and the discharged volume are derived in relation to a given discharge flow. These relations are shown in figure 4. This diagram shows cumulatively the relative duration of the given discharge flow in relation to the total duration of discharge over a period of 25 years. In the same diagram is also shown cumulatively the relative volume that was discharged with the given flow. The diagram in figure 4 was derived from a detention tank behind weir B in case I (storage 2 mm).

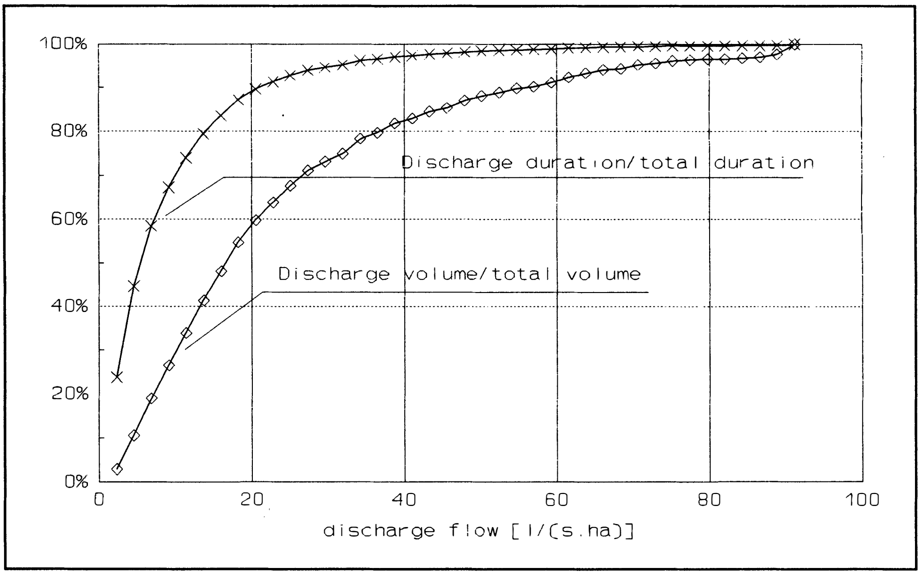


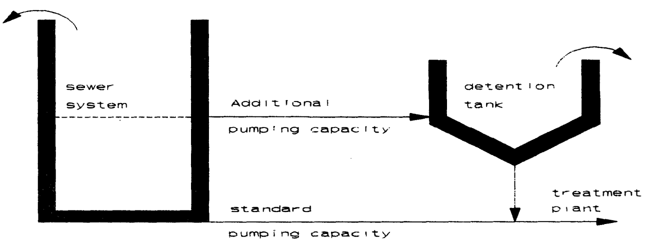
Figure 4. ***Distribution of relative discharge volume and flow duration in relation to occurring discharge flow (De Bilt, 1955-1979)***

The discharge flow in the diagram of figure 4 is related to the total catchment area of the sewer system. The diagram shows that a given discharge flow of less or equal to 20 l/(s·ha) occurs over a period of 90% of the total discharge duration. During this time period 60% of the total overflow volume has been discharged. This understanding establishes the possibility of deriving efficiencies.

The dynamic approach enables to simulate the hydraulic performance of detention tanks during a longterm period. With this principle efficiencies can be obtained in contrast to the traditional approach. Moreover the dynamic design principles can be used to take into account the disturbances of settling processes due to the varying of the time and storm dependent flow regime in detention tanks, e.g. the resuspension of deposited sediments through high flow velocities.

Case III Real time control with additional pumping capacity

In a sewer system with several weirs it may not be desirable to construct a detention tank downstream of each weir. An attractive solution to this problem is to introduce additional pumping capacity that discharges into a central detention tank. This detention tank discharges into less vulnerable surface water. The figure below shows the principle of additional pumping capacity.



The reduction of pollution is achieved by pumping the resuspended sludge and pollutants to the central detention tank during the filling of the sewer system. Other features of additional pumping capacity are:

- more flexibility in the selection of the building site; for instance near a sewage treatment plant, in the vicinity of suitable surface water, away form residential areas;
- simple and less expensive construction of the detention tanks; building on ground level is possible without the necessity of covering.

The design of a detention tank that is filled by pumps has the advantage that the surface load is constant. The theoretical settlement efficiency is known if the size of the tank has been determined. However, the assessment of storage capacity, start and stoplevels of pumping and the pump capacities is less simple.

Special attention must be given to the real time control of the extra pumps so that no storm water is unnecessarily pumped from the sewer system into the detention tank. If the pump starts too early the detention tank will be used too often. Because of this the frequency of cleaning increases and the total overflow volume may be influenced. This understanding leads to high startlevels of pumping and high pumping capacities (1 mm/h to 3 mm/h) in order to obtain the desired reduction of loads. The size of the tank is determined by a filling time of 1 to 1.5 hours.

As example two pumping scenarios are investigated:

scenario 1: *fixed startlevel pumping capacity: the pump is working while the sewer system is being filled;*

scenario 2: *intelligent control: pump starts at a fixed level and remains working until the detention tank is filled. If the sewer system is still being filled the pump may start again at a higher level, if the tank was already filled, or it remains working until the filling of the sewer system has stopped.*

The results of the two scenarios are shown in figure 5. The calculations are based on a sewer system with 7 mm storage and 0.7 mm/h pumping capacity. The size of the tank is equal to 3 mm storage. The results of the pumping scenario's are compared with the discharge of a sewer system with and without a detention tank behind each weir.

The diagram of figure 5 shows that the application of scenario 1 with a fixed startlevel of pumping leads to an important reduction of discharge volume out of the sewer system when the additional pumping capacity increases. In this case the discharge volume of the tank also increases. The total amount of volume discharged has not considerably changed in relation to the reference sewer system without detention tank.

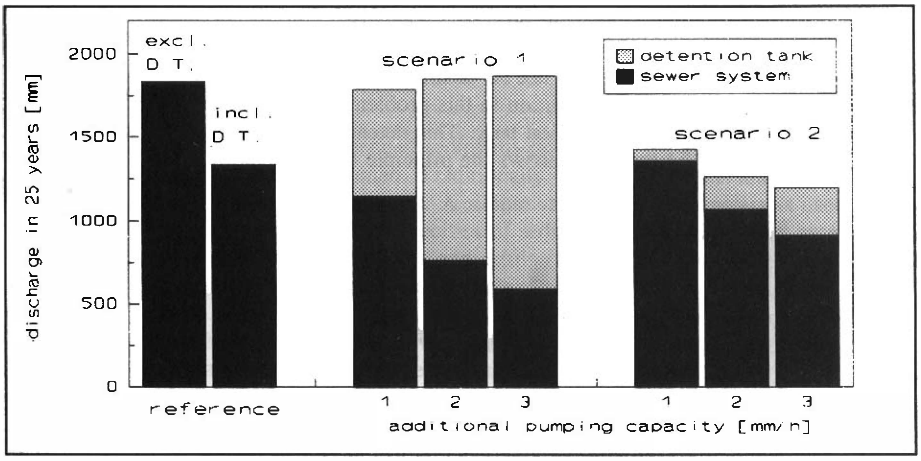


Figure 5. *Impact of additional pumping capacity on discharge volumes of a sewer system*

The principle of control in accordance with scenario 2 agrees with the discharge of the reference sewer system with detention tanks behind weirs. The total amount of volume discharged has decreased in comparison with scenario 1. Especially the discharge of the tank has been reduced.

The discharge volumes are significantly affected by the chosen pumping scenario. The optimisation of these scenarios can be done with dynamic design, because the full course of rainfall is used and hence the filling process of the sewer system can be simulated.

Case IV Additional storage capacity in rush fields

The efficiency of detention tanks may not meet stricter standards regarding receiving water impact. Stricter regulations of water boards may result in the construction of additional storage. In this case basins with large storage capacity may be considered.

Concrete detention tanks are not the most appropriate solution to create more than 2 mm or 3 mm storage. Less expensive solutions are retention ponds or rush fields with relatively large storage capacity (10 mm). Rush fields (Lageveen et al.,1990) are developed to be a more natural alternative to detention tanks. The operation of rush fields is not only based on a relatively large storage capacity of 10 mm, but also on a high sediment retention efficiency, the dilution with clean water and the purification of nutrients by the rushes. The discharged storm water remains in the rush field for a period of one to two weeks. Within this period the retained storm water is circulated and aerated to establish reduction of oxygen demanding pollutants and nutrients. After this period the retained storm water is gradually drained off to surface water.

Normally an increase of storage implies an increase in the emptying time of a sewer system. Not only the availability of storage is influenced, but also sewer treatment plants will be taxed longer. The treatment efficiency could reduce because of the dilution of sewage. Because the retained storm water in rush fields is gradually drained off to surface water, the large storage capacity of rush fields does not influence the efficiency of a treatment plant.

The assessment of a sewer system with a large storage capacity is not possible without the knowledge of the sequence of storms. The sequence of storms significantly influences the availability of storage. Time series of rainfall can give insight into this sequence.

CONCLUSIONS

The dynamic design of ancillary structures using the computer programs EXTRAN/GM and NIVO/GM is based on continuous simulations with longterm time series of rainfall. The principles of dynamic design establish a better insight of the performance, i.e. the flow and the storage capacity, of sewer systems during a short and longterm period.

The application of dynamic design is not only restricted to the design of detention tanks as the traditional approach, but also the overall performance of sewer systems is considered. The introduction of real time control with additional pumping capacity and the application of flow routing strategies through adjusting the crest levels of weirs and/or removing weirs can be used not only for the reduction of the number of detention tanks but also for directing the selection of building sites of these ancillary structures.

The dynamic approach significantly exceeds the traditional design method for the calculation of distribution of discharge volumes and flows. Therefore the dynamic approach is suitable to meet new regulations regarding receiving water impact. Ancillary structures, e.g. detention tanks, can be used more efficiently because of the analysis of discharge characteristics per overflow location .

ACKNOWLEDGEMENT

The authors wish to thank mr. G.B. Lemmen for his useful contribution to this paper.

REFERENCES

Buishand, T.A., Acker, J.B.M. van, Luijtelaar, H. van, (1991). Analyse van kwartiersommen van de neerslag. H_2O (24),1991, nr. 11.

Coördinatie Commissie Uitvoering Wet Verontreiniging Oppervlaktewateren, (in press, 1992). Aanbevelingen voor het beleid en de vergunningverlening met betrekking tot overstortingen uit rioolstelsels en regenwaterlozingen, CUWVO,'s-Gravenhage.

Huber, W.C., Heaney, J.P., Nix, S.J., Dickinson, R.E., Polman, D.J. (1984). Storm Water Management Model, User's manual, University of Florida, Department of Environmental Engineering Sciences, Gainesville, Florida USA.

Lageveen, R., Mook, J.C., Graaff, C.Th. de, (1990). Randvoorzieningen riolering: case Houten. 2e Nationale Rioleringscongres Riolering en Waterkwaliteit, Aquatech 1990, NVA, Rijswijk.

Luijtelaar, H. van, Ganzevles, P.P.G., (1990). Bewerking 15-minuten neerslagreeksen ten behoeve van dimensionering van rioolstelsels en randvoorzieningen. 2e Nationale Rioleringscongres Riolering en Waterkwaliteit, Aquatech 1990, NVA, Rijswijk.

Nationale Werkgroep Riolering en Waterkwaliteit, (1989). Eindrapportage en evaluatie van het onderzoek 1982 -1989, NWRW, Staatsuitgeverij, 's-Gravenhage.

Nationale Werkgroep Riolering en Waterkwaliteit, (1989). Neerslag-inloop-overstortmodel, NWRW publicatie 4.3, Staatsuitgeverij, 's-Gravenhage.