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Sewer Systems and Climate Change

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Abstract

In this article the impact of climate change on the overflows of sewer systems is assessed. The emphasis is on the overflows of combined sewer systems. The purpose is twofold: first, to obtain a first-order estimate of the impact of climate change on overflows of sewer systems; and second, to obtain insight into the relevant meteorological variables that are important with respect to climate change. A reservoir model is used to assess the impact of climate change on several combinations of storage capacity and pumpovercapacity of the sewer system. A time series of precipitation depth for Lelystad, with time steps of five minutes, is used as a base case for comparison. Two types of scenarios are used to assess the sensitivity for climate change: artificial climate scenarios and scenarios based on the analogous climate method.

1 Introduction

Sewer systems in the Netherlands can be divided into two groups, combined sewer systems and separate sewer systems. In combined systems, rainwater and waste water from households and industries are transported to the water treatment plant by one and the same water conduit. In contrast, in separate systems, rainwater and waste water are transported by two separate conduits. The rainwater is discharged into the open water of the urban area and the waste water is transported to the water treatment plant. According to a study of the national working group on sewer systems and water quality, NWRW, the majority (90%) of the sewer systems in the Netherlands is of the combined type (NWRW, 1984). Therefore the discussion in this article will be restricted to this type.

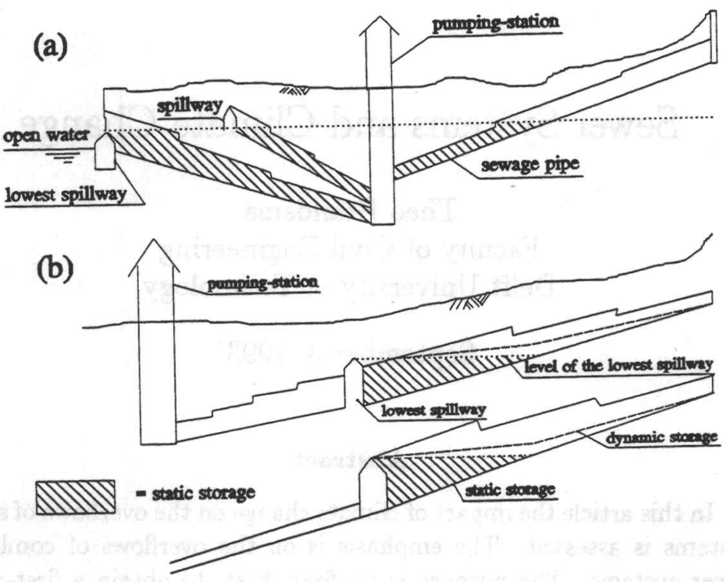

Figure 1: Combined sewer systems in: (a) flat areas and (b) sloping areas (after Van den Herik and Kooistra, 1973).

1.1 Present Design Practice and Problems

Functioning of the system The principles of the functioning of combined sewer systems are illustrated in figure 1. This figure shows that the functioning of combined systems in flat areas differs from their functioning in sloping areas. Figure 1a shows a sewer system in a relatively flat area (as is the case in most parts of the Netherlands) and figure 1b shows a sewer system in a sloping area. In both cases the polluted water in the system is pumped by a pumping station to the water treatment plants. When the inflow into the system exceeds the pumping capacity, the storage of the system is4 filled and above the crest level of the spillway the water is spilled to the open water.

The main difference between the two systems is in the storage of water in the system. Two types of storage can be distinguished. The first type is static storage, which contains the storage of water below the lowest crest level, and the second type of storage is dynamic storage which contains all the storage of water above the lowest crest level. The system in figure 1a contains a relatively large amount of static storage and the dynamic storage can be neglected, whereas the system in figure 1b contains a relatively small amount of static storage and the dynamic storage cannot be neglected.

As the larger part of the Netherlands satisfies the description of figure 1a, the rest of the discussion is restricted to this system.

The pumping capacity available to pump excess water (e.g., rain water) from the system to the treatment plants is denoted pumpovercapacity (i.e., total pumping capacity minus dry-weather-flow). In general this capacity is not sufficient to transport the total inflow during showers. Therefore the system contains a certain storage capacity to store the water in the system until it can be transported to the treatment plants. Despite the pumpover-capacity and the storage capacity, it occurs often (e.g., ten times per year) that the system gets filled completely. To avoid discharge of polluted water onto the streets, the system contains spillways. When the water level in the system rises above the crest level of these spillways the polluted water is discharged into the open water system.

The problem of overflow of polluted water via spillways is greatest in situations where the spillway discharges into stagnant or semi-stagnant open water. The larger the receiving open water or the larger the flow rate in this water, the smaller the negative impact of the polluted water on the environment (Gast, 1989). The NWRW (1984) concluded that the majority of the spillways in the Netherlands discharges into stagnant or semi-stagnant waters. In those cases the overflow of polluted water will have a negative impact on the receiving water-ecosystems.

Gast (1989) concludes from the NWRW-study, that the most important measure to reduce the impact of emissions is to flush the receiving open water, or to move the spillways to locations where the open water has a larger flow rate.

Objective of design The main objective of a combined sewer system is to collect waste water and rain water, and to transport the water to the treatment plants. The design of the system should be such that discharge of polluted water onto the streets is prevented and that the overflow of polluted water via the spillways is minimized.

Design practice and problems The most important feature of sewer system design in the Netherlands, as compared to other countries, is that the system is designed for storage and not for hydraulics. In general, existing sewer systems in the Netherlands meet the hydraulic criteria, but the water in the system has to be stored in the system until it is pumped to the water

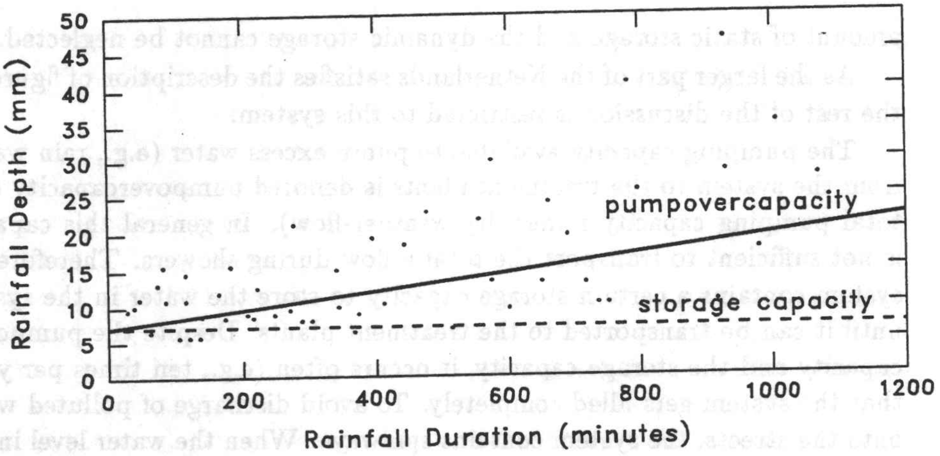

Figure 2: Principle of the Kuipers-graph.

treatment plants. Therefore, the storage, and not hydraulics, governs the design of sewer systems.

The present design practice is based on: 1) the relationship between the emission of polluted water (a mixture of rain water and waste water) and the theoretical overflow frequency; and 2) the relationship between the theoretical overflow frequency (computed with the so-called 'dotted graph of Kuipers', further referred to as Kuipers-graph) and the actual overflow frequency.

The principle of the Kuipers-graph is illustrated in the fictive graph of figure 2. The original of the Kuipers-graph contains all the showers with a precipitation depth > 4 mm in De Bilt in the period 1926–1962. All showers in this 37-year period are represented by dots in the original graph. In the fictive graph of figure 2, the dashed horizontal line represents the storage capacity of the sewer system and the solid sloping line represents the pumpovercapacity. For a system with a fixed storage capacity and pumpovercapacity, the dots above the sloping line represent the (theoretical) overflows. Counting all the dots above the sloping line and dividing the total by 37 gives the average annual overflow frequency for a sewer system with a specified storage and pumpovercapacity.

The application of the Kuipers-graph is based on the following assumptions:

- A shower a is period of uninterrupted rainfall;
- The rainfall intensity is constant during a shower;

- The maximum storage capacity is available at the beginning of a shower;
- The pumpovercapacity is in operation from the beginning of the shower and it is constant;
- The inflow into the system equals the rainfall (i.e., the runoff coefficient = 1), and there is no transformation;
- Only paved areas discharge into the sewer system.

The thus computed average annual overflow frequency, the so-called theoretical overflow frequency, serves as a measure for the average annual load of pollution discharged into the open water via the spillway. In general water quality administrators require the theoretical overflow frequency to be ≤ 7 overflows per year. If the theoretical overflow frequency is > 7, the system should be adapted by increasing the storage capacity or the pumpovercapacity. In practice one will decide to increase the storage capacity rather than the pumpovercapacity because increasing the pumpovercapacity is, in general, more expensive than increasing the storage capacity as an increase of the pumpovercapacity also requires adaption of the water treatment plants.

This method of computing the average annual overflow frequencies as a measure of the average annual load of pollution has been subject to a lot of criticism. For instance, the NWRW (1986) compared the theoretical overflow frequencies with the measured frequencies for the towns of Oosterhout, Loenen and Bodegraven. It appeared that the measured overflow frequencies were higher than the theoretical overflow frequencies, namely 7%, 27% and 14% for Oosterhout, Loenen and Bodegraven, respectively. Although these results seem reasonably good, it appeared, however, that in about 50% of all cases the computed overflow did not correspond to the actual overflow.

The reasons for the discrepancy between computed and actual overflow have to be found in the assumptions underlying the model. The NWRW (1986) concluded that the cause of the discrepancy is mainly in the following assumptions: 1) maximum storage capacity is available at the beginning of a shower; and 2) only paved areas, with an assumed runoff coefficient = 1, discharge water into the sewer system. Because the errors made on account of these two assumptions, frequently compensate each other, the result of computed overflow frequency corresponds fairly well to the actual overflow frequency.

Another problem is the relationship between the load of pollution and the average annual overflow frequency. Gast (1989) presents the following factors affecting the load of pollution, as found in the NWRW-study:

- The intensity of a shower;
- The features of the paved surface, which influence the volume and the composition of the load of pollution;
- The features of the unpaved area (it appeared that, especially in sloping areas, unpaved areas contribute to the inflow of the sewer system);
- The construction and maintenance of the sewer system, which influence the load of pollution.

The general conclusion of the NWRW was that reduction of the overflow frequency, by increasing the storage capacity and/or the pumpovercapacity, requires relatively large investments and yields proportionately little effect. It is better (if possible) to move the spillways to larger open waters with a higher flow rate or, if movement of spillways is not possible, to flush the receiving open waters.

At present the above mentioned methodology of computing the theoretical overflow frequency is still being used. New methods have been proposed but are not yet widely accepted and applied. For instance Van den Berg and Ven (1977) take into account rainfall loss and the transformation of net-rainfall to inflow into the sewer system. The result is a more realistic estimate of overflow frequencies (for flat areas). The method has been further developed by Van de Ven (1989).

Although the above-mentioned improvements result in better estimates of overflow frequencies and related parameters they do not give a better insight into the load of pollution during an overflow of the system.

An attempt to produce a model describing the load of pollution in sewer systems is made by Sluis and Van der Velde (1991). However, this model has not yet been sufficiently validated. It seems that in this area of hydrology much research has still to be done before adequate and generally accepted models can be developed.

Discussion From the foregoing, it appeared that the emphasis in sewer system design in the Netherlands is on the load of pollution from the system, spilled into the open water. It appeared that present-day design practices are not sufficient to describe transport of pollution in sewer systems. Although some new design methods are being developed, no new generally accepted model exists.

For the purpose of the study of this article it seems appropriate to use a modified version of the Kuipers-graph, taking into account the course of the showers and the time between showers. As overflow variables the following parameters will be used: overflow frequency, overflow duration, overflow volume, and maximum overflow intensity.

1.2 Climate change and sewer systems

Climate change may significantly alter the depth and distribution of rainfall and therefore the overflows of sewer systems in urban areas.

As the process of transformation of rainfall into surface runoff in paved urban areas is a process with a very short response time (in the order of five minutes), the interest with relation to climate change, is mainly in the change of extremely intense showers. The fact that the load of pollution from sewer systems is found to be mainly determined by high intensity showers (Gast, 1989) is another reason to look mainly for changes in extremes. However, at present it is very uncertain how rainfall depth and distribution will change as a result of climate change.

1.3 Scope and objectives

The emphasis in this research is on the impact of climate change on the overflows of combined sewer systems in flat areas in the Netherlands. The research is limited by the present-day sewer system design practice, which is in a state of transition. The most recent methods will not be used in this research, because the purpose of this research is to give a first order approximation of the sensitivity of overflows of sewer systems to climate change. Further, the interest is not in absolute changes but in relative changes (or differences).

The objectives of the research are as follows:

- To develop a method for assessing the impact of climate change on combined sewer systems in the Netherlands;
- To assess the sensitivity of overflows of sewer systems to changes in climate;

- To obtain insight into the relevant meteorological variables that are important with respect to climate change.

2 Method of research

2.1 Introduction

Although sewer system design is in a state of transition, present-day design practices and design standards are still based on the empirical approach, namely the Kuipers-graph. As outlined in section 1, the annual overflow frequency computed with the Kuipers-graph corresponds fairly well to the actual annual overflow frequency. However, it appeared that in about 50% of the overflows the computed overflow did not correspond to the actual overflow. Because the errors made as a results of the assumptions underlying the Kuipers-graph (see section 1) frequently compensate each other, the computed annual overflow frequency still corresponds fairly well to the actual overflow frequency. However, because the physical basis of this Kuipers-graph is so weak, this method cannot be used to assess the changes in overflow variables as a result of climate change.

The study of the NWRW resulted in a new view on sewer system design. The NWRW (1986) concluded that the present empirical approach is no longer an adequate basis for sewer system design. The NWRW also found that, among other things, the following features of the system are important:

- The overflow intensity;
- The total overflow volume;
- The features of the receiving water.

On the basis of those features of the system, it is decided here that the impact of climate change on overflows of sewer systems will be assessed using a reservoir model with time dependent input. As a first order approximation this model may give useful information on the response of the system to climate change. In the following, the model is described in detail.

2.2 The reservoir model

Background information Use of reservoir models for sewer system design is considered admissible for all flat areas in the Netherlands (Van de Ven, 1989; NWRW, 1986; Koot, 1977). The model used for the Kuipers-graph (figure 2) is also a reservoir model. However, the reservoir model used for the present research is quite distinct from the model for the Kuipers-graph. The major difference is in the rainfall input into the model. In contrast to the model used for the Kuipers-graph the following features have been taken into account:

1. The course of a shower as a function of time;

2. The succession of showers;

3. The change in storage as a function of time.

This can be accomplished by using a real time series of rainfall data as input for a computer model which calculates the water balance of the reservoir after each time step. This method, with some modifications, was also used by other authors (e.g., Van de Ven, 1989; Van den Berg and Ven, 1977).

Several important simplifications underlying the Kuipers-graph are now omitted. These are: 1) a shower is a period of uninterrupted rainfall; 2) the rainfall intensity is constant during a shower; and 3) the maximum storage capacity is available at the beginning of a shower.

The resulting model is much more realistic than the model used for the Kuipers-graph. However, the model is still rather crude. For instance, it does not take into account rainfall losses of precipitation by infiltration, evaporation and depression storage. Also, the model is not capable of predicting the actual load of pollution spilled into the open water. Instead, overflow variables serve as a measure for the load of pollution. For instance, overflow frequency is an important output variable, as it indicates the frequency of discharge of pollution into the open water system (or ecosystem). The overflow volume is an important measure for the dimensions of the spillways and the dimensions of the open water courses. The maximum overflow intensity is also an important output variable, as it serves as a measure for the load of pollution (the larger the intensity the more turbulence, and the more material will detach itself from the roofs, streets and sewer pipes).

Formulation of the conceptual model The first step in the procedure of modeling is the construction of a conceptual model of the related system. The conceptual model consists of a set of assumptions that reduce the real problem and the real system to a simplified version that is acceptable in view of the objectives of the modeling.

The real problem of the flow of water and material in and to a sewer system is very complicated; it is three-dimensional and transient. The system of metaled surfaces, roofs and sewer pipes is complicated, as are the boundary conditions and the initial conditions. Therefore, several assumptions have to be made before the construction of a model.

In section 2.1 a model has already been selected, namely the reservoir model. The following assumptions have been made for this model:

1. The sewer system behaves as a lumped system;
2. The input is deterministic with time steps of five minutes;
3. The full pumping capacity operates from the beginning of a shower;
4. Precipitation is in the form of rainfall;
5. Rainfall losses are neglected;
6. Delay effects are neglected;
7. Evaporation is neglected;
8. Only metaled surfaces contribute to the runoff;
9. Overflows between the start of the filling of the reservoir and the moment the reservoir is empty again, are considered to belong to one overflow.

Formulation of the mathematical model After the formulation of the conceptual model, this model must be expressed in mathematical terms. For the formulation of the mathematical model consider the reservoir depicted in figure 3.

The model can be formulated by the following continuity equation

$$\frac{dS}{dt} = P(t) - Q(t) - poc \tag{1}$$

where S is storage [L], $P(t)$ is net precipitation [LT^{-1}], $Q(t)$ is overflow ($Q(t) = 0$ if $S < S_{max}$) and poc is pumpovercapacity [LT^{-1}] which is constant as long as there is water in the reservoir. In this approach the sewer system is modeled by a reservoir with a maximum storage S_{max} [L]. The input consist of the net precipitation depth with discrete time steps. If the maximum storage S_{max} is exceeded, overflow $Q(t)$ will occur. The main

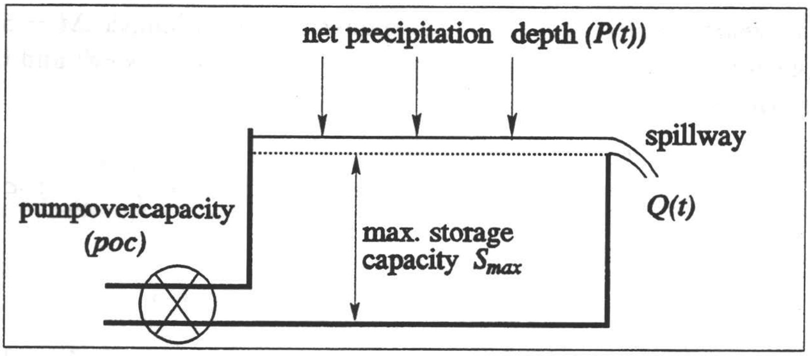

Figure 3: The reservoir model

interest is in the statistical features of the overflow $Q(t)$ as a function of S_{max}, *poc* and the changes in the precipitation distribution, $P(t)$.

Equation 1 contains two unknown quantities, namely $S(t)$ and $Q(t)$, therefore an additional relationship is needed. This relationship concerns the discontinuity for $S = S_{max}$. If $S = S_{max}$ and $P(t) > poc$ then $\frac{dS}{dt} = 0$ and the difference of $P(t)$ and *poc*, $P(t) - poc$, will flow out of the system as $Q(t)$.

Including the initial condition at $t = 0$, $S\,|_{t=0} = 0$, the complete mathematical formulation of the problem becomes

$$\frac{dS}{dt} = P(t) - Q(t) - poc, \text{ if } 0 \leq S \leq S_{max} \tag{2}$$

$$Q(t) = \begin{cases} P(t) - poc & \text{if } S = S_{max} \text{ and } P(t) \geq poc \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

and

$$S\,|_{t=0} = 0 \text{ and } 0 \leq S \leq S_{max}$$

Solution of the mathematical model Once the mathematical model has been formulated, the problem can be solved by using either an analytical or a numerical method. In this case an analytical method is not feasible because of the irregular temporal distribution of the input, $P(t)$, to the system. Instead a numerical method is employed for solving the mathematical model.

Because the input to the system, $P(t)$, is available only at discrete time intervals, it is necessary to reformulate the continuity equation (equation 1 on a discrete time basis. In this case the input consists of a rainfall record of 15 years divided into intervals, indexed by j, of length $\Delta t = 5$ minutes. Equation 2 can be rewritten as $dS = P(t)dt - Q(t)dt - poc\, dt$ and integrated over the j^{th} time interval to give

$$\int_{S_{j-1}}^{S^j} dS = \int_{(j-1)\Delta t}^{j\Delta t} P(t)dt - \int_{(j-1)\Delta t}^{j\Delta t} Q(t)dt - \int_{(j-1)\Delta t}^{j\Delta t} poc\, dt \tag{4}$$

or

$$S_j - S_{j-1} = P_j - Q_j - poc_j,\ j = 1, 2, \ldots \tag{5}$$

where P_j and Q_j are the depth of rainfall and the depth of outflow in the j^{th} time interval, respectively. In equation 5, all variables have dimensions [L]. If the increase in storage $(S_j - S_{j-1})$ is denoted by ΔS_j, then one writes $\Delta S_j = P_j - Q_j - poc_j$.

If the initial storage at time $t = 0$ equals S_0 then $S_1 = S_0 + P_1 - Q_1 - poc$, $S_2 = S_1 + P_2 - Q_2 - poc$, and so on. By substituting for intermediate values, one obtains

$$S_j = S_0 + \sum_{i=1}^{j} (P_i - Q_i - poc_i) \tag{6}$$

which is the discrete time continuity equation. Taking into account the conditions specified in equation 2, a simple computer program was written to solve equation 6.

Definitions The method used in this article is illustrated in figure 4. As an example the impact of a storm in the night of July 9–10, 1984, is given for a reservoir with parameters $poc = 1.5$ mm/hour and $S_{max} = 4$ mm. It may be noted from this figure that the storm caused an overflow of polluted water into the surrounding surface water. The total precipitation depth of the storm was 25.7 mm, causing an overflow of 14.1 mm. The difference of these two was pumped to the water treatment plants and amounted 25.7 − 14.1 = 11.6 mm. The maximum overflow intensity was 2.7 mm/5 minutes (or 32.4 mm/hour).

In the following the average annual values and average monthly values of some overflow variables are defined. When the average annual value is used, the following is meant (consider, e.g., the average annual overflow frequency, off):

$$off = 1/15 \sum_{j=1}^{15} off^j$$

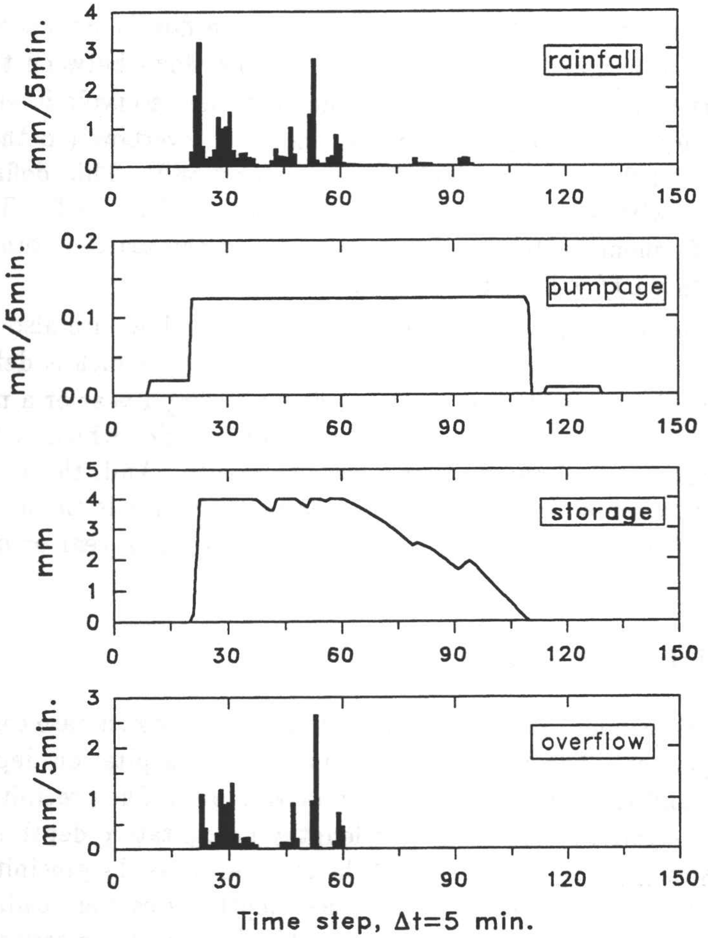

Figure 4: Operation of the reservoir model, with parameters $poc = 1.5$ mm/hour and $S_{max} = 4$ mm, during a storm in the night of July 9–10, 1984.

where off^j is the overflow frequency in year j, and j corresponds to the years 1970–1984, $j = 1$ for 1970, $j = 2$ for 1971, and so on. When the average monthly value is used the following is meant:

$$off_k = 1/15 \sum_{j=1}^{15} off_{j,k} \quad k = 1, \ldots, 12$$

where $off_{j,k}$ is the overflow frequency in year j for month k, where $k = 1$ corresponds to January, $k = 2$ to February, and so on.

In the Netherlands the average annual overflow frequency of the system is an important measure. In this research an overflow is defined as the event in which water flows over the spillway. All overflows between the moment the reservoir begins to fill and the moment the reservoir is empty again are considered to belong to one and the same overflow (so the overflows in figure 4 belong to one and the same overflow). This definition is in agreement with the definition given by Van de Ven, 1989. The average overflow frequency is further denoted as off. In this article, both the annual and monthly off will be considered.

Some other measures connected with the overflow, are also considered. First, the average overflow volume, denoted as ofv, which is defined as the average of the total volume of the overflows during a year or a month. Second, the average overflow duration, denoted as ofd, which is the average total duration of all overflows in a year or month. And, third, the average maximum overflow intensity, denoted as $mofi$, which is the average maximum overflow depth in a five minute interval during a year or month.

2.3 Meteorological data

For the assessment of the sensitivity for climate change a base case is needed for comparison. The base case consists of the precipitation depth series of Lelystad and the corresponding overflow variables. The precipitation depth series of Lelystad is one of the two lengthy precipitation depth series in the Netherlands with short time steps (the other series is the precipitation series of De Bilt). The Lelystad precipitation depth series was readily available at the Delft University of Technology. The length of the series is 15 years (1970–1984). The original series was measured with a variable time step by event-sense registration (for details see Van de Ven, 1989). For the purpose of this study the series has been transformed into a series with a fixed time step of five minutes.

2.4 Assessment of sensitivity for climate change

Several methods can be applied to assess the sensitivity of the model for climate change. In this article, the sensitivity for climate change will be assessed using artificial climate scenarios and scenarios based on the analogous climate method. For the assessment with the analogous climate method only the overflow frequency (off) will be considered.

Artificial climate scenarios For the artificial climate scenarios a distinction is made between the so-called multiplicative method and the additive method. The multiplicative method is a method in which the data in a meteorological time series are multiplied by a factor; consequently, both the location and shape of the frequency distribution of precipitation depth changes. The additive method is a method in which a certain quantity is added to all values in an existing time series of a meteorological variable; consequently, only the location of the frequency distribution changes.

The emphasis here is on the multiplicative method, as the multiplicative method is the most straightforward and the most commonly used of the two methods. The multiplicative method is widely used for imposing a climate change on an existing precipitation series. The multiplicative method is also rather straightforward, therefore, the major part of the results relate to the multiplicative method.

Both in the multiplicative and the additive method artificial changes are imposed on the precipitation depth series of Lelystad. In the multiplicative method the series will be multiplied by several factors and functions to obtain several scenarios. For instance, a change in annual precipitation depth of 20% is obtained by multiplying all precipitation depth values in the series by 1.2. The effect of a scenario will by assessed by running the model with the changed precipitation series and comparing the output with the output of the original series.

In contrast with the multiplicative method, in the additive method an amount of rainfall is added to or subtracted from the precipitation depth values. Whereas the multiplicative method is straightforward the additive method involves some subjective choices. For example, it must be known how many intervals with precipitation occur in a given year. Therefore an arbitrary threshold value must be specified to determine whether or not an interval is a precipitation interval.

Mainly because of the subjective assumptions involved in using the additive method, this method is only used to evaluate the results of the multiplicative method. It will then be possible to assess the sensitivity of using another method to impose the same change in total annual rainfall depth.

Analogous climate method The analogous climate method involves the use of precipitation depth series of existing climates, different from the climate in the Netherlands. It is assumed that these precipitation depth are series are analogous to the series expected as a result of climate change. Un-

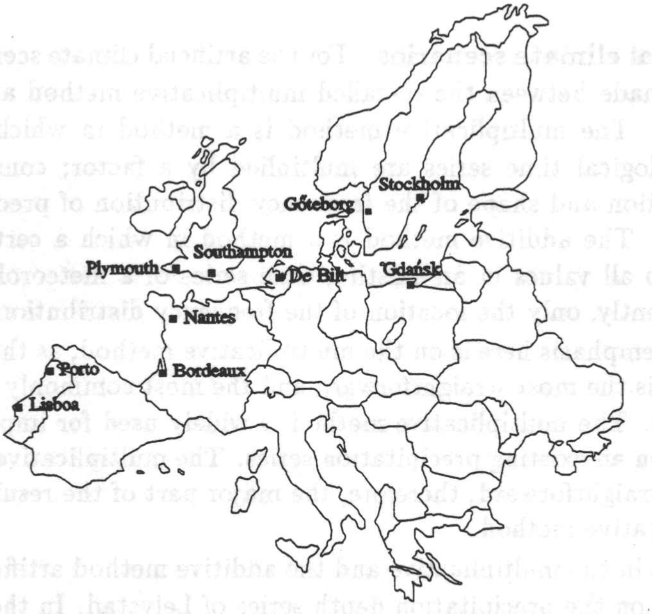

Figure 5: Cities in Europe for which daily precipitation depth data were obtained for the period 1970–1990.

fortunately, with respect to sewer systems, precipitation depth series with short time steps (about five minutes) could not be obtained within the scope of this project. As mentioned before, such series are scarce and often difficult to obtain, even in the Netherlands. However, time series of daily precipitation depth data have been obtained for several cities in Europe. Those cities are presented in figure 5. The data were obtained from the meteorological services in the relevant countries.

Inferences for sewer system design can be drawn based on these daily precipitation depth data. This can be done by assuming that the current relationship between the overflow frequency and the number of days with precipitation depth above a certain threshold (dependent upon the dimensions of the sewer system) remains equal. At present this assumption seems reasonable, especially because the interest here is in a first estimate of the impact of climate change.

A relationship between the overflow frequency on the one hand and the number of days with precipitation depth above a certain threshold and the amount of precipitation above that threshold on the other, was found by Buishand (1985). For De Bilt he found a clear relationship between those variables. Using this relationship he calculated overflow frequencies for other

i	poc	S_{max}	i	poc	S_{max}	i	poc	S_{max}
1	0.5	2	13	1.5	2	25	2.5	2
2	0.5	4	14	1.5	4	26	2.5	4
3	0.5	6	15	1.5	6	27	2.5	6
4	0.5	8	16	1.5	8	28	2.5	8
5	0.5	10	17	1.5	10	29	2.5	10
6	0.5	12	18	1.5	12	30	2.5	12
7	1.0	2	19	2.0	2	31	3.0	2
8	1.0	4	20	2.0	4	32	3.0	4
9	1.0	6	21	2.0	6	33	3.0	6
10	1.0	8	22	2.0	8	34	3.0	8
11	1.0	10	23	2.0	10	35	3.0	10
12	1.0	12	24	2.0	12	36	3.0	12

Table 1: Combinations of pumpovercapacity, *poc*, and reservoir storage, S_{max}, for which results are obtained.

towns in the Netherlands. For his calculations he made use of the Kuipers-graph.

The approach of Buishand has also been adopted in this article; however, four differences from the method of Buishand must be noted: 1) the point of departure is not De Bilt but Lelystad; 2) the overflow frequencies have not been calculated with the Kuipers-graph but with the reservoir model with the precipitation depth series of Lelystad as input; 3) the amount of precipitation above the threshold has not been taken into account; and 4) it has been taken into account that the magnitude of the threshold is dependent on the parameters of the sewer system; a tight system (high overflow frequency) will have a low threshold and a spacious system (low overflow frequency) will have a high threshold.

3 Results

The results in this section refer to 36 combinations of the pumpovercapacity, *poc*, and the reservoir storage, S_{max}. The combinations of *poc* and S_{max} are presented in table 1. For each climate scenario results have been obtained for all of the 36 combinations.

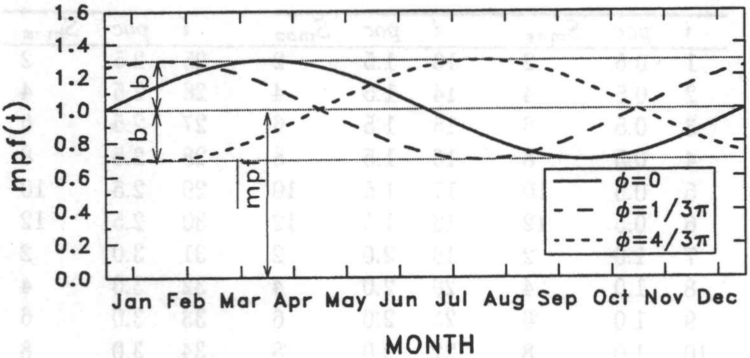

Figure 6: Principle of a sinusoidal change imposed on the precipitation time series.

3.1 Impact of multiplicative scenarios

The various climate scenarios in this section are denoted by case numbers, case 1, case 2, etc. These cases will subsequently be described. A summary of the features of the cases is given in table 2.

Case 0 Case 0 is the base case, which means that the model is run with the original precipitation time series of Lelystad (15 years of data with 5 minute time intervals).

Cases 1 to 5 In cases 1 to 5 an average annual increase or decrease was imposed on the time series of Lelystad. This was achieved by multiplying all precipitation values in the series with a constant multiplication factor, further denoted as the average annual multiplication factor $\overline{mpf}$. The factor $\overline{mpf}$ takes on the following values: 0.8, 0.9, 1.1, 1.2, and 1.4.

Cases 6 to 15 In cases 6 to 15, the effect of seasonal variation of the multiplication factor was taken into account. This was done by imposing a sinusoidal change on the time series. The principle is further illustrated in figure 6. The sinusoidal function in this figure can be described by the following equation

$$mpf(t) = \overline{mpf} + b\sin(2\pi t + \phi) \tag{7}$$

where $mpf(t)$ is the multiplication factor for a specified month, whereby $t = 1/24, 3/24, 5/24, \ldots$, corresponds to January, February, March, ..., respectively; $\overline{mpf}$ is the average annual multiplication factor; b is the amplitude of the sine wave; and ϕ is the phase shift of the sine wave where

case	$\overline{mpf}$	b	ϕ	**case**	$\overline{mpf}$	b	ϕ
0	1.0	-	-	8	1.0	0.2	$1/3\pi$
1	0.8	-	-	9	1.0	0.2	$4/3\pi$
2	0.9	-	-	10	1.0	0.3	$1/3\pi$
3	1.1	-	-	11	1.0	0.3	$4/3\pi$
4	1.2	-	-	12	0.8	0.2	$1/3\pi$
5	1.4	-	-	13	0.8	0.2	$4/3\pi$
6	1.0	0.1	$1/3\pi$	14	1.2	0.2	$1/3\pi$
7	1.0	0.1	$4/3\pi$	15	1.2	0.2	$4/3\pi$

Table 2: Features of the cases under consideration

$\phi = (0, 1/6\pi, 2/6\pi, 3/6\pi, \ldots, 2\pi)$. In figure 6 three lines are shown with $\overline{mpf} = 1.0$, the amplitude $b = 0.3$ and phase shifts $\phi = 0$, 1/3 and $4/3\pi$.

Results for the case with $\overline{mpf} = 1.0$ and $b = 0.1$ indicated that in most of the 36 reservoir combinations, as listed in table 1, maxima in the overflow variables occur at a phase shift of $\phi = 4/3\pi$ and minima at a phase shift of $\phi = 1/3\pi$ (this is especially true for the annual maximum 5 minutes overflow intensity and the annual overflow frequency). The phase shift $\phi = 4/3\pi$ corresponds to maxima in the months July-August, and the phase shift $\phi = 1/3\pi$ corresponds to minima in the months July-August. This is evident because most of the rainfall and most of the heavy thunderstorms in the Netherlands occur in the summer months. For this reason the rest of the calculations was carried out with only those two phase shifts, representing a maximum and minimum case.

The average annual multiplication factor, $\overline{mpf}$, equals 1.0 for case 6 to 11, 0.8 in case 12 and 13 and 1.2 in case 14 and 15; the amplitude of the sine wave, b, equals 0.1 in case 6 and 7, 0.2 in case 8 and 9 and case 12 to 15, and 0.3 in case 10 and 11; and the phase shift of the sine wave, ϕ, equals $1/3\pi$ for the even cases and $4/3\pi$ for the odd cases.

The results of the base case, case 0, are given in figure 7. In this figure, graphs of the following overflow variables are given: 1) the annual overflow frequency, off; 2) the annual overflow volume, ofv; 3) the annual overflow duration, ofd; and 4) the maximum annual overflow intensity in a 5 minute time interval, $mofi$. Contour lines are drawn through the results, using the method of minimum curvature.

The results of cases 1 to 15 are given in appendix A as figures 17 to

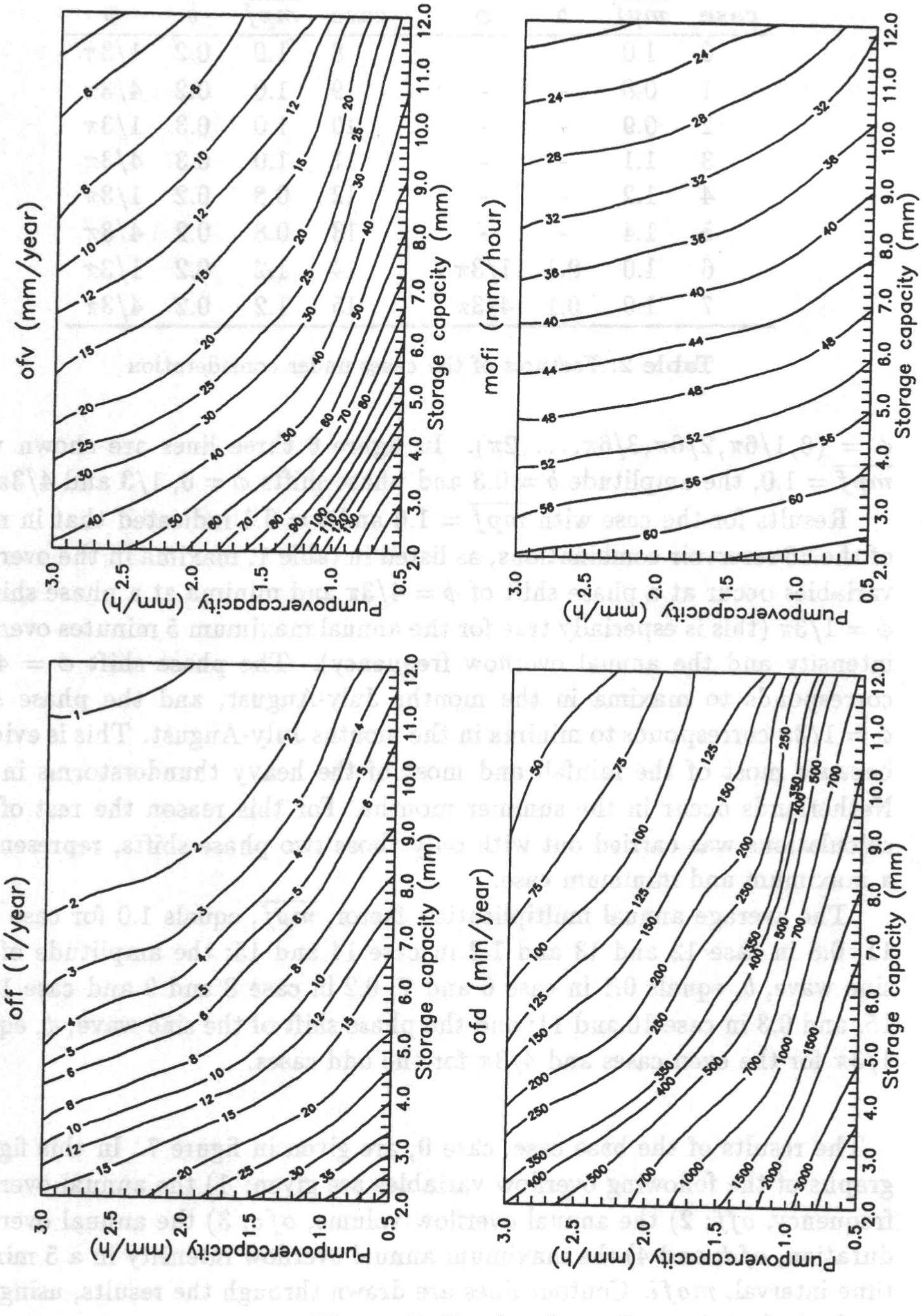

Figure 7: Results of case 0.

31, respectively. These results are also presented as figures with contour lines; however, the overflow variables are now expressed as a proportion of the overflow variables of the base case. The following notation is used to represent those proportions

$$F^* = \frac{off(X)}{off(\text{Lelystad})}, \quad V^* = \frac{ofv(X)}{ofv(\text{Lelystad})},$$

$$D^* = \frac{ofd(X)}{ofd(\text{Lelystad})}, \quad I^* = \frac{mofi(X)}{mofi(\text{Lelystad})}$$

where X stands for the case number.

Discussion of results From the results in figure 7, the base case, the following can be noted:

1. The off, ofv, and ofd are a function of both the pumpovercapacity, *poc*, and the maximum storage capacity, S_{max}, with the absolute effects of changing *poc* or S_{max} being largest for small values of *poc* and S_{max};
2. The maximum annual overflow intensity, $mofi$, is a function of both *poc* and S_{max}, and changing *poc* and/or S_{max} has roughly the same effect throughout the domain investigated.

It should also be noted that the results of the base case agree fairly well with the results obtained by Van de Ven (1989).

The differences between off, ofv, and ofd on the one hand, and $mofi$ on the other, can be explained by the fact that $mofi$ is governed by the heaviest storm in a year causing overflow, while the computation of the other variables is governed by all storms in a year causing overflow. That the effects of changing *poc* or S_{max} are largest for small values of those parameters is because the larger the reservoir parameters the rarer the storms which will cause overflow of the system.

The fact that raising the pumpovercapacity, *poc*, has about the same effect upon $mofi$ as raising the storage capacity S_{max} is caused by the time scale of heavy storms, which is about one hour. On the one hand, an increase in S_{max} is immediately available at the beginning of the storm; on the other hand, an increase in *poc* releases the same amount of water from storage as the increase in S_{max} only after some time, say $t = t_1$. If a storm starts at $t = t_0$ and this storm causes an overflow at time $t = t_2$, and $t_2 \approx t_1$, then an increase in S_{max} will have about the same effect upon $mofi$ as increase in *poc*. Consider, e.g., a reservoir with $poc = 1.0$ mm/h and $S_{max} = 4.0$ mm, with $mofi = 56$ mm/h. Increasing *poc* with 1 mm/h to $poc = 2.0$ mm/h gives $mofi \approx 52$ mm/h, a reduction of 7%. About the same decrease in *mofi* is obtained by increasing S_{max} with 1 mm to $S_{max} = 5$ mm.

The results of cases 1 to 5, figures 17 to 21 of appendix A, show the sensitivity of the system to changes in the multiplication factor. From these figures the following can be noted:

1. Was to be expected, the figures for F^*, V^*, and D^* compare fairly well with each other for each case;
2. F^*, V^*, D^* and I^* are larger than $\overline{mpf}$ for $\overline{mpf} > 1$ and smaller than $\overline{mpf}$ for $\overline{mpf} < 1$;
3. F^*, V^*, D^* and I^* differ within the domain of reservoir parameters, where F^*, V^*, D^* and I^* are closest to 1 for small values of *poc* and S_{max}.

With the figures of F^*, V^*, D^* and I^*, the effects of imposed climate change can be derived for any set of parameters in the investigated domain. The change in annual precipitation can now be compared with the corresponding change in overflow variables using figures 17 to 21 of appendix A. For instance, consider four sewer systems with the following reservoir parameters: (a) $poc = 1.5$ mm/h and $S_{max} = 6.0$ mm; (b) $poc = 1.5$ mm/h and $S_{max} = 5.0$ mm; (c) $poc = 2.0$ mm/h and $S_{max} = 3.0$ mm; and (d) $poc = 1.0$ mm/h and $S_{max} = 2.0$ mm; the results for these systems are given in figure 8 in graph a to d, respectively. In this figure a dashed bold line is drawn for each graph; this line represents an imaginary case in which $\overline{mpf} = F^*, V^*, D^*$, or I^*. The most important general feature of increasing or decreasing the annual rainfall with the $\overline{mpf}$, is that in both cases the value of the increase or decrease in overflow variables is much larger. In case of decreasing rainfall this is a positive effect, but in case of increasing rainfall this is a negative effect.

From figure 8 also the following features can be noted:

1. The proportionality of F^*, V^*, D^*, and I^* with $\overline{mpf}$ depends on the magnitude of the reservoir parameters, where the proportionality is larger for small reservoir parameters (tight system);
2. I^* is more proportional to $\overline{mpf}$ than the other variables;

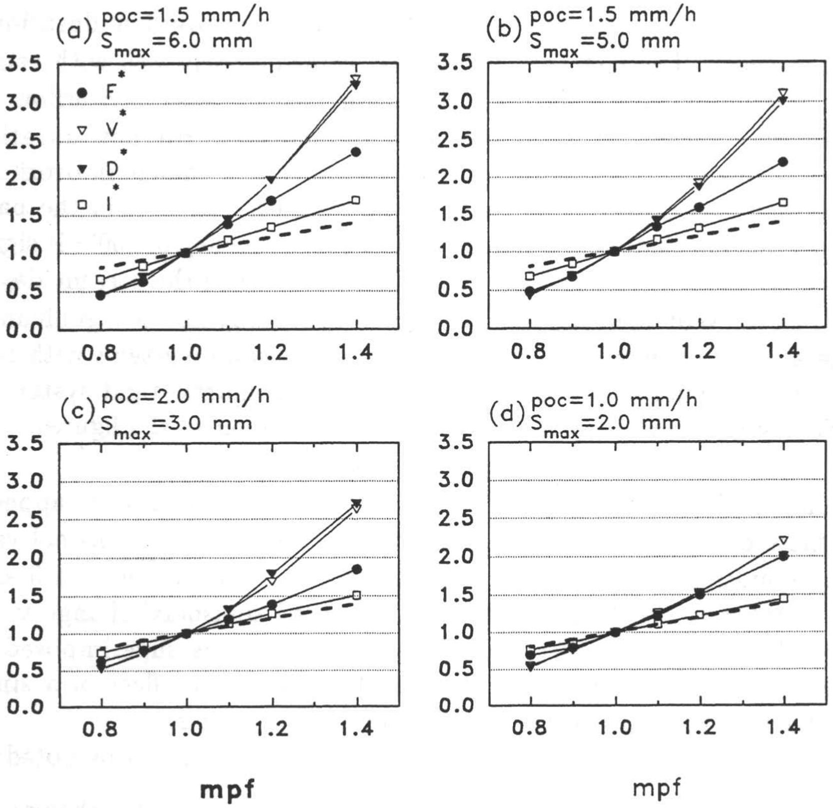

Figure 8: Summary of the results for four sewer systems: (a) $poc = 1.5$ mm/h and $S_{max} = 6.0$ mm; (b) $poc = 1.5$ mm/h and $S_{max} = 5.0$ mm; (c) $poc = 2.0$ mm/h and $S_{max} = 3.0$ mm; and (d) $poc = 1.0$ mm/h and $S_{max} = 2.0$ mm; the dashed bold line in each figure represents an imaginary line where $\overline{mpf} = F^*$, $\overline{mpf} = V^*$, $\overline{mpf} = D^*$, or, $\overline{mpf} = I^*$, respectively.

3. V^* and D^* coincide fairly well with each other;
4. F^* is always in between I^* on the one side and V^* and D^* on the other side.

The fact that I^* corresponds fairly well with $\overline{mpf}$, especially for small reservoir parameters, can be explained by the course of the overflow. The smaller the reservoir parameters, the more the course of the overflow will follow the course of the rainfall. The fact that F^* is always smaller than V^* and D^* can be explained by the definition of those variables. For example, when rainfall increases it is possible that the overflow frequency (off) remains the same, whereas the overflow volume (ofv) and the overflow duration (ofd) will increase. The fact that V^* and D^* coincide fairly well with each other can also be explained by their definition. An increase in overflow volume will nearly always be accompanied by an increase in overflow duration.

It is obvious that the practical significance of a change in overflow variables depends on the magnitude of the overflow variables in the base case (figure 7). For instance, a change in overflow frequency of 100% is significant when the present-day off is, e.g., 10/year, but when the present-day off is, e.g., 1 or 2/year then the same change of 100% may not be significant at all. Therefore, a change in precipitation will affect sewer systems with reservoir parameters lying in the lower left corner of the figures (tight systems) more seriously than those lying in the upper right corner of the figures.

The results of cases 6 to 15 are given in figures 22 to 31 of appendix A. In these cases the sensitivity of the overflow variables to seasonal variation of the multiplication factor is studied. In cases 6 to 11 $\overline{mpf} = 1.0$ and only the amplitude and phase shift of the imposed sinusoidal change varies. In cases 12 and 13 the effect of a sinusoidal change is superimposed on the effect of an $\overline{mpf}$ of 0.8; and in cases 14 and 15 the effect of a sinusoidal change is superimposed on the effect of an $\overline{mpf}$ of 1.2.

From figures 22 to 27 (cases 6 to 11) the following can be noted:

1. Although the average annual $mpf = 1$, a sinusoidal change in mpf may increase or decrease the overflow variables, being the greatest for great amplitudes of the sinusoidal change; a decrease corresponds to a minimum in the months July-August and an increase corresponds to a maximum in the months July-August;

2. The relative changes are nearest to 1 for small reservoir parameters, i.e., in the lower left corner of the figures.

The effects mentioned under 1 and 2 are caused by the unequal distribution of storms and the intensity of storms over the year. Therefore, it is of major importance to know how a future climate change will be distributed over the year.

From figures 28 to 31 (cases 12 to 15) in appendix A the following can be noted:

1. The seasonal variation in mpf (with mean=0), superimposed on a $\overline{mpf}$ different from 1, may enlarge or reduce the effect of a constant mpf only different from 1;

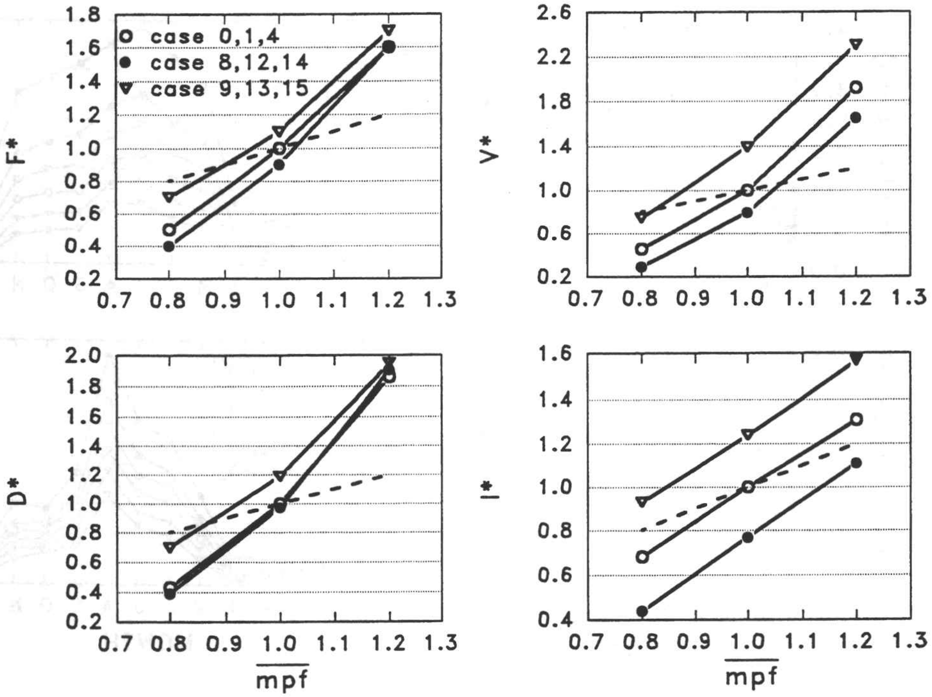

Figure 9: The effect of seasonal variation in *mpf* on F^*, V^*, D^*, and I^*.

2. The effect of seasonal variation, superimposed on $\overline{mpf}$, is largest for $mofi$.

For a sewer system with *poc* = 1.0 mm/h and S_{max} = 4.0 mm these two points are illustrated in figure 9. In this figure the cases with seasonal variation in *mpf*, having an amplitude of 0.2, are compared with the corresponding cases without seasonal variation, namely case 0, 1 and 4 ($\overline{mpf}$ = 1.0, 0.8, and 1.2, respectively).

3.2 Monthly variation of overflow variables

In the foregoing section it was found that seasonal variation affected the overflow variables of the model considerably. Therefore, in this section the seasonal variation of the overflow variables is further studied.

As an example consider a sewer system with reservoir parameters *poc* = 1.0 mm/h and S_{max} = 4.0 mm. For almost all cases the mean monthly values of the overflow parameters are given in figures 10 to 12. In all figures

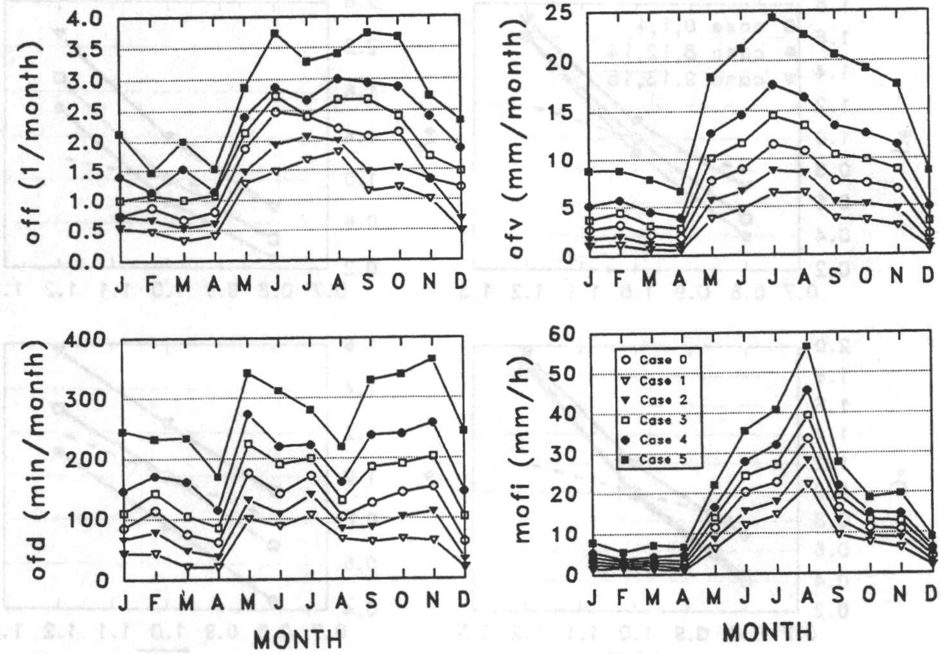

Figure 10: Monthly variation of overflow variables for the cases 0 to 5.

the base case is given for comparison. Further, the variation of F^*, V^*, D^* and I^* for case 5 ($\overline{mpf} = 1.2$) is given in figure 13 for several cases.

Discussion of the results From the results in the figures 10 to 12 it appears that the seasonal variation is visible for all overflow variables, with the strongest variation in *mofi*, which is caused by the occurrence of convective storms in the warm summer months. Furthermore, imposing a seasonal variation may strengthen the seasonal pattern or may diminish (or even fade out) the seasonal pattern.

From figure 13 it can be noted that F^*, V^*, D^*, and I^* vary strongly over the year, with the greatest relative changes in those periods which contribute less to the annual F^*, V^*, D^*, and I^*.

In conclusion, the results emphasize the importance of knowing the seasonal variations of a future climate change in obtaining realistic estimates of overflow variables for sewer systems in the Netherlands.

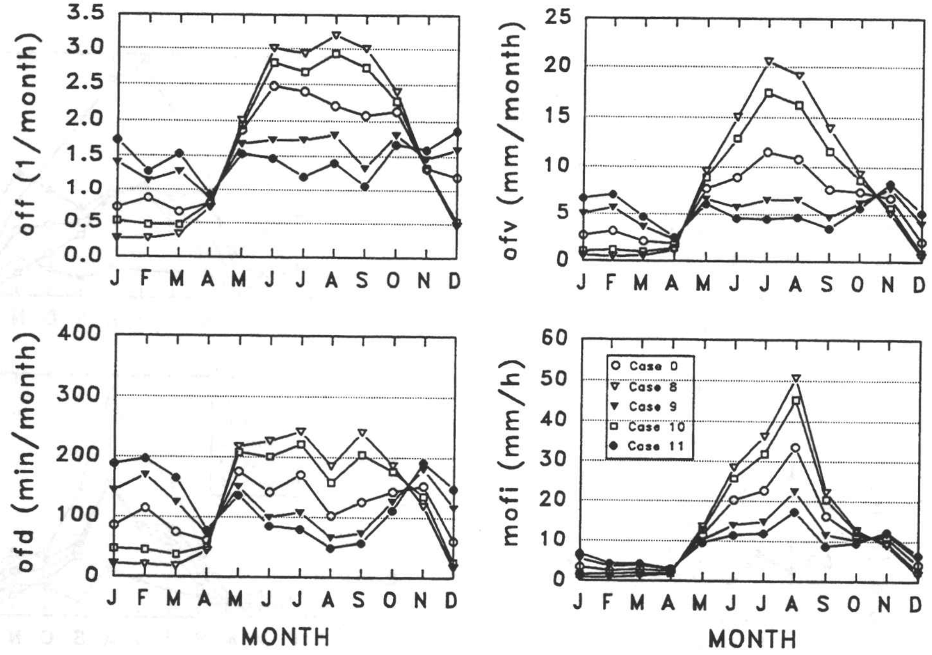

Figure 11: Monthly variation of overflow variables for case 0 and the cases 8 to 11.

3.3 Impact of additive scenarios

In the foregoing it was assumed that the imposed climate change could be obtained by simply multiplying all precipitation values in the existing precipitation series by a multiplication factor, *mpf*. However, as noted before, other methods to obtain the annual increase or decrease may also fit. For instance, an annual increase in precipitation depth may also be obtained by an increase in the number of storms or by distributing the annual increase in precipitation depth equally over all, or part, of the intervals with precipitation.

In this section, the effect of distributing the annual increase in precipitation depth equally over all or part of the intervals with precipitation is investigated. The cases thus obtained are called additive cases as the annual precipitation depth change is obtained by adding precipitation to the existing precipitation intervals and not by multiplication.

The purpose is twofold: first, to illustrate that the same change in annual precipitation depth can be distributed in different ways on an existing meteorological time series; and, second, to investigate the importance of the

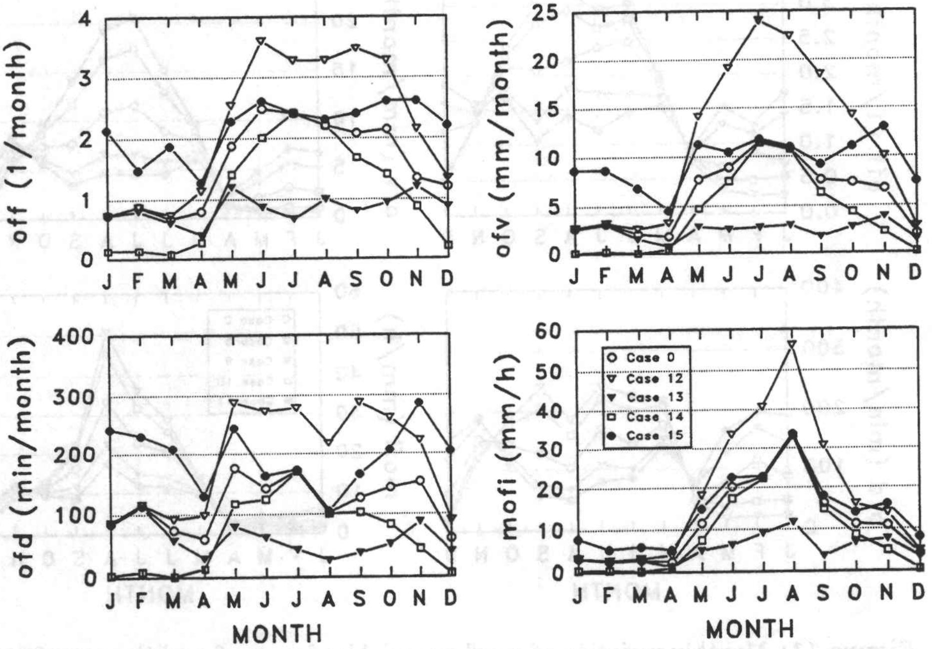

Figure 12: Monthly variation of overflow variables for case 0 and the cases 12 to 15.

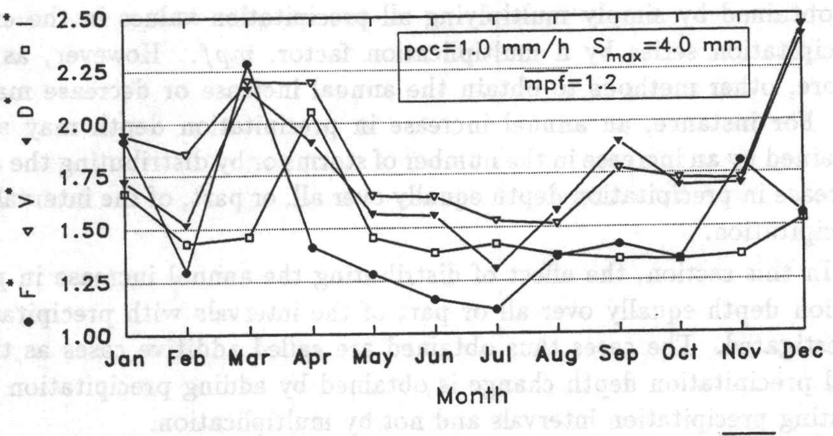

Figure 13: Monthly variation of F^*, V^*, D^*, and I^* for case 5 ($\overline{mpf} = 1.2$) for a system with reservoir parameters $poc = 1.0$ mm/hour and $S_{max} = 4.0$ mm.

case	$\Delta P(\%)$	Threshold (mm)
16	20	0
17	20	0.05
18	20	0.2

Table 3: Description of additive cases.

method of implementing a climate change on a meteorological time series.

As noted before, the main difference between the multiplicative and additive method is in the standard deviation (shape) of the precipitation distribution. In the multiplicative method the relative change in the standard deviation equals the relative change in the mean, which means that the distribution of precipitation values widens or narrows (depending on whether the change is an increase or a decrease). On the other hand, when the additive method is used, the standard deviation remains the same and only the mean of the distribution of precipitation depth values increases or decreases.

As the material in this section only serves to illustrate the effect of using another method of implementing a climate change, only one change in annual precipitation depth will be considered, namely an annual increase in precipitation depth of 20%. The results of case 4 ($\overline{mpf} = 1.2$, see figure 20 of appendix A) will be compared with the cases in this section.

Three additional cases are considered in this section. The characteristics of these cases are given in table 3. The increase in annual precipitation depth is equally distributed across all 5-minute intervals with precipitation depth greater than the threshold value. For instance, a threshold value equal to 0 mm means that the annual increase in precipitation is equally distributed over all 5 minute intervals with precipitation depth $P > 0$ mm. Likewise, a threshold value equal to 0.05 mm means that the annual increase is equally distributed over all intervals with precipitation depth $P > 0.05$ mm.

It should be noted that the original precipitation depth series of 15 years length was measured with variable time intervals. When the rainfall intensity was great, the accompanying duration of the measurement intervals was short (e.g., 1 minute) and when the rainfall intensity was small, or even zero, the measurement interval was long (e.g., 30 minutes). Converting this series to a series with a constant time step of 5 minutes results in a series with too many intervals with precipitation. Therefore, besides case 16 also cases 17 and 18 are considered.

case	F^*	V^*	D^*	I^*
4	1.58	1.92	1.86	1.31
16	1.08	1.12	1.19	1.01
17	1.49	1.60	2.13	1.03
18	2.00	2.63	2.32	1.12

Table 4: Comparison of overflow variables for several methods of implementing a 20% annual increase in precipitation depth on the existing precipitation series for a sewer system with reservoir parameters $S_{max} = 5.0$ mm and $poc = 1.5$ mm/h.

Discussion of results The results are given in figures 32 to 34 of appendix A. Comparing these figures with figure 20 of appendix A ($mpf = 1.2$) the following can be noted

1. The magnitude of the threshold value is extremely important for the magnitude of the overflow variables;
2. The maximum 5 minute overflow intensity for the additive method, $mofi$, is rather insensitive to the increased rainfall;
3. The greater the threshold value, the more the shapes of the figures correspond to those in figure 20

The first point can be illustrated by taking a specific sewer system with, e.g., $S_{max} = 5.0$ mm and $poc = 1.5$ mm/h; the results are given in table 4. From this table it appears that the amount of intervals with precipitation is of major importance for the outcome of the model. Whereas the figures for F^*, V^* and D^* of case 4 and case 18 agree fairly well, the agreement for I^* is bad for all cases. It is obvious that the large difference in $mofi$ between the methods (multiplicative and additive) lead to completely different effects on the overflow variables.

In summary, the method for implementing a climate change on an existing precipitation series with 5 minute time intervals, determines the outcome of the model to a great extent. Whereas the multiplicative method is rather straightforward, the additive method requires an arbitrary choice of the threshold value.

3.4 Analogous climate method

In this section the results for the analogous climate method will be presented. First, the present relationship between the annual overflow frequency (off_j)

and the number of days in year j with precipitation depth greater than the threshold, will be determined for Lelystad. Second, the relationship found will be used to calculate the average annual overflow frequencies (off) for the analogous climates relative to Lelystad.

3.4.1 Results for Lelystad

The results for Lelystad, the base case (case 0), were already presented in figure 7. For Lelystad the so-called Pearson correlation coefficients (R) are calculated for off_j and the amount of days with precipitation depth above a specific threshold in year j for each of the 36 combinations of poc and S_{max} (see table 1).

For each sewer system, twenty-five values for the threshold, varying from 1 to 25 mm, were used to find the best fit of a linear regression equation of the following form

$$y_{ij} = a_i x_{ij} + b_i \tag{8}$$

where y_{ij} is the number of overflows in year j for system number i, x_{ij} is the number of days with precipitation depth greater than the threshold (dr_i) in year j for system number i, and a_i and b_i are the regression coefficients for system number i. The explaining variable x_{ij} depends on the threshold dr_i; the threshold is chosen in such a way that: 1) the intercept b_i equals zero; and 2) an optimal fit is obtained. As a result the overflow frequency equals zero when there are no heavy storms.

The results for each sewer system are given in table 5. All correlation coefficients are significant at the 99% confidence level. This means that the probability that a correlation coefficient of at least the given value is obtained when there is no linear association in the population between off_j and the number of days with precipitation depth greater than the threshold is less than 0.01.

3.4.2 Results for the analogous climates

The average annual overflow frequency, off, for the various analogous climates can now be calculated making use of table: 5 and the following equation

$$\hat{y}_i = \hat{a}_i x_i \tag{9}$$

where $\hat{y}_i$ is the estimated off for system number i and for one of the stations, and x_i is the average of the annual number of days with precipitation

i	R_i	dr_i	$\hat{a}_i$	i	R_i	dr_i	$\hat{a}_i$	i	R_i	dr_i	$\hat{a}_i$
1	0.89	6	1.28	13	0.70	6	0.72	25	0.67	6	0.43
2	0.94	6	0.69	14	0.84	6	0.32	26	0.73	6	0.19
3	0.93	8	0.61	15	0.76	10	0.35	27	0.74	9	0.15
4	0.92	10	0.54	16	0.74	15	0.47	28	0.71	13	0.17
5	0.92	13	0.61	17	0.68	16	0.32	29	0.84	15	0.17
6	0.87	14	0.49	18	0.64	17	0.25	30	0.68	17	0.21
7	0.87	6	0.95	19	0.69	6	0.57	31	0.76	6	0.38
8	0.86	6	0.46	20	0.82	6	0.25	32	0.66	6	0.15
9	0.79	9	0.46	21	0.73	9	0.19	33	0.66	9	0.12
10	0.91	16	1.07	22	0.81	10	0.12	34	0.73	12	0.12
11	0.88	19	1.00	23	0.87	22	0.54	35	0.82	17	0.24
12	0.95	19	0.62	24	0.79	13	0.09	36	0.70	17	0.17

Table 5: Pearson correlation coefficients (R_i) for the annual overflow frequency and the number of days with precipitation depth $> dr_i$ mm; the threshold for the precipitation depth (dr_i); and the estimated regression coefficient ($\hat{a}_i$) for the 36 systems.

depth $> dr_i$ mm for the station concerned. The overflow frequencies for the analogous climates and De Bilt are now expressed as a fraction of the overflow frequencies for Lelystad according to

$$F^* = \frac{off(X)}{off(\text{Lelystad})} \tag{10}$$

where X refers to the station concerned for the analogous climates and De Bilt. De Bilt is also considered as a means for comparison. The results for each analogous climate and De Bilt are presented in figures 14 to 16.

It is of interest to know the statistical significance of the calculated values for F^*. Therefore, it was tested whether or not the average of the number of days with precipitation $> dr_i$ is statistically different from Lelystad. This was done by means of a two-sided t-test. For the comparison of De Bilt and Lelystad the mutual correlation of the precipitation depth series was taken into account. The observed significance levels are given in table 6. In this case, the observed significance level is the probability that a difference at least as large as the one observed would have arisen if the averages were really equal. Thus, the smaller the observed significance level, the more certain we are that the averages are statistically different.

The observed significance levels also hold for the results, because the overflow frequencies are obtained by a linear transformation of the average

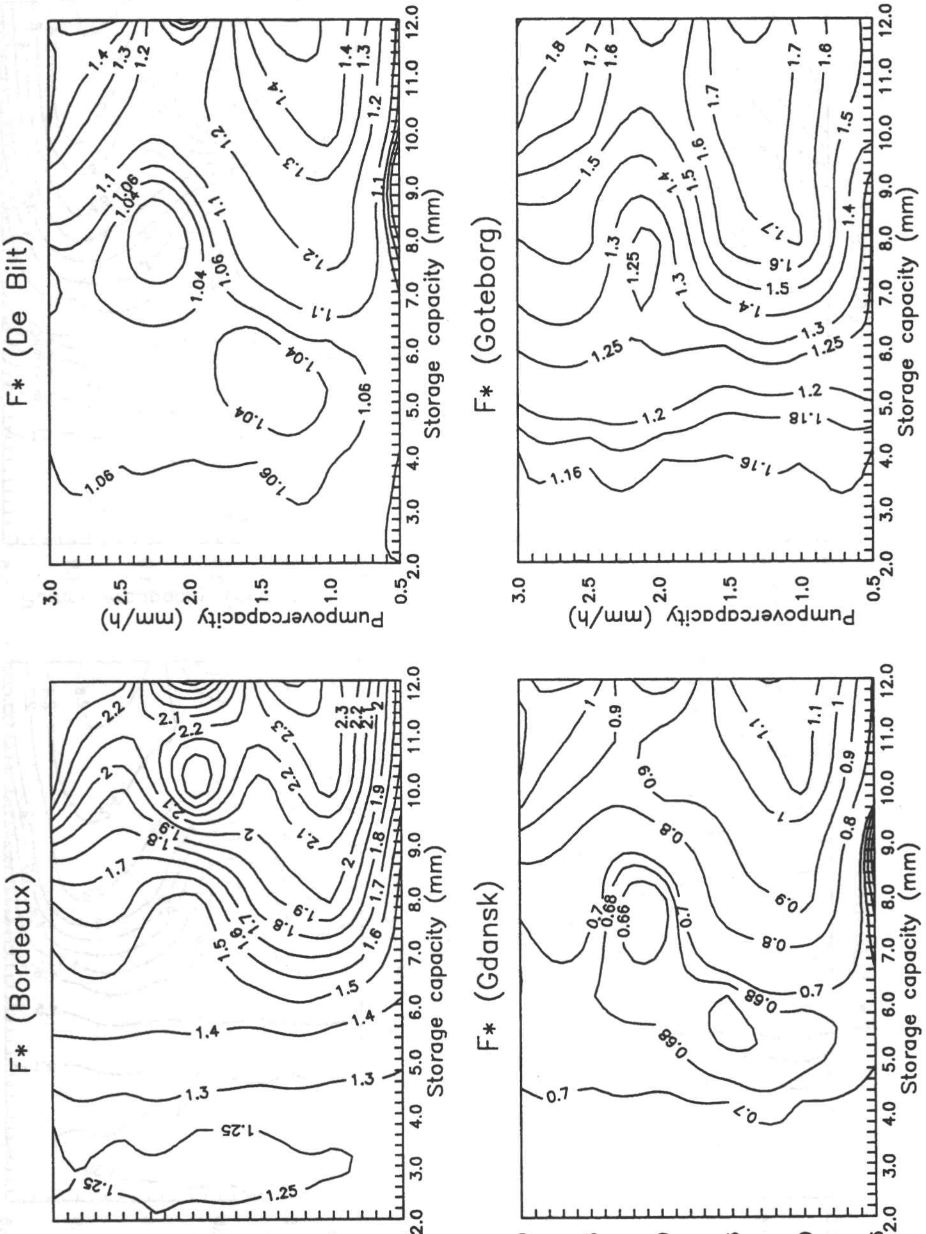

Figure 14: Results for the relative overflow frequencies for the analogous climates and De Bilt.

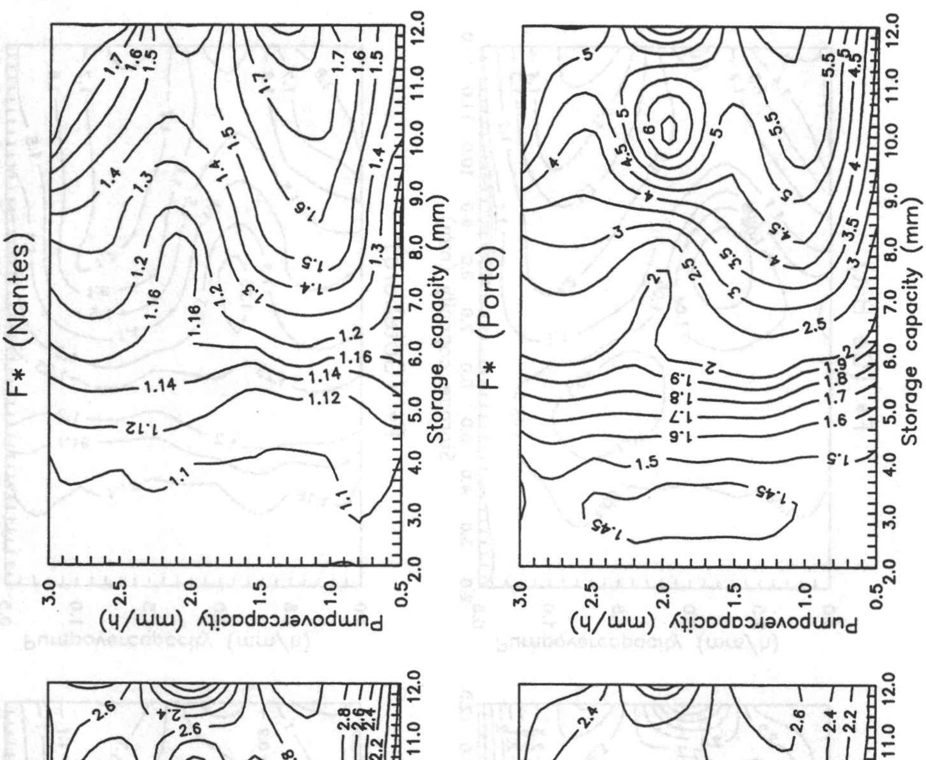

Figure 15: Results for the relative overflow frequencies for the analogous climates and De Bilt (continuation of figure 14).

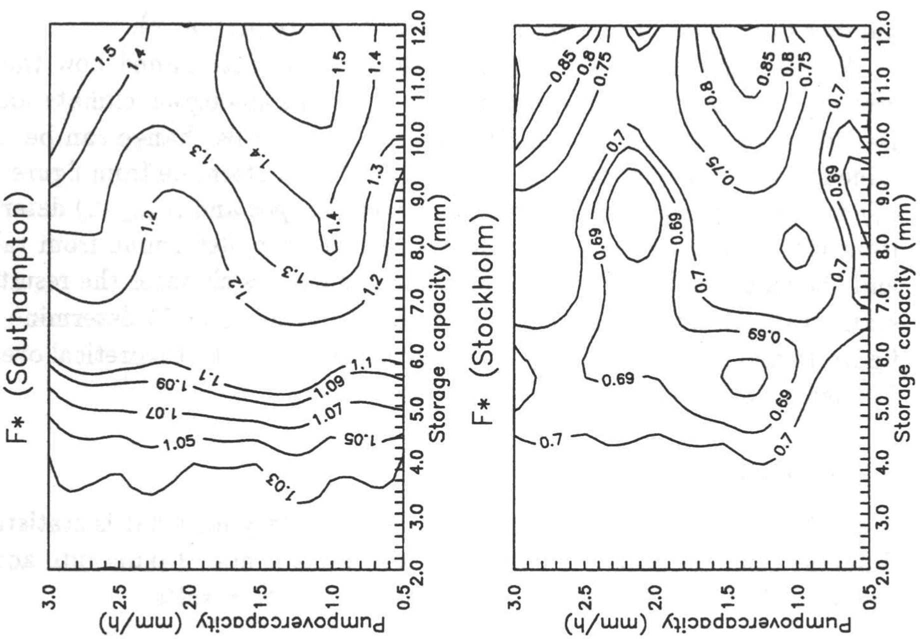

Figure 16: Results for the relative overflow frequencies for the analogous climates and De Bilt (continuation of figure 14).

dr	Bord.	Bilt	Gdan.	Göte.	Liss.	Nant.	Plym.	Port.	Sout.	Stock
6	0.00	0.31	0.00	0.03	0.09	0.21	0.00	0.00	0.61	0.00
8	0.00	0.45	0.00	0.01	0.68	0.09	0.00	0.00	0.22	0.00
9	0.00	0.59	0.00	0.01	0.21	0.10	0.00	0.00	0.20	0.00
10	0.00	0.82	0.00	0.03	0.15	0.17	0.00	0.00	0.16	0.00
12	0.00	0.60	0.04	0.01	0.00	0.06	0.00	0.00	0.05	0.04
13	0.00	0.78	0.07	0.01	0.00	0.07	0.00	0.00	0.04	0.04
14	0.00	0.28	0.18	0.01	0.00	0.05	0.00	0.00	0.06	0.07
15	0.00	0.46	0.44	0.00	0.00	0.02	0.00	0.00	0.08	0.12
16	0.00	0.23	0.72	0.00	0.00	0.01	0.00	0.00	0.02	0.18
17	0.00	0.03	0.64	0.01	0.00	0.00	0.00	0.00	0.01	0.49
18	0.00	0.02	0.59	0.02	0.00	0.00	0.00	0.00	0.03	0.25
19	0.00	0.04	0.49	0.02	0.00	0.00	0.00	0.00	0.03	0.18
22	0.00	0.04	0.86	0.09	0.00	0.15	0.00	0.00	0.20	0.18

Table 6: Observed significance levels for which the average of the annual number of days with precipitation depth > dr_i differs from Lelystad.

number of days with precipitation depth $> dr_i$ (equation 9).

For an arbitrary sewer system it can now be determined how the theoretical overflow frequency changes for a certain analogous climate and for De Bilt. In addition the statistical significance of this change can be determined. The following steps must be followed: 1) determine from figure 7 the off for the present situation for the parameters poc and S_{max}; 2) determine from table 5 the threshold for the precipitation; 3) determine from table 6 and the value for the threshold, for which analogous climates the results are statistically different from the results for Lelystad; and 5) determine from figure 14 and figure 15 and equation 10 the change in the theoretical overflow frequency (off), taking into account step 3.

3.4.3 Discussion of the results

A significance level of 0.10 is a reasonable boundary for what is statistically different from the results for Lelystad and what is not. Taking into account this boundary, the following can be noted from the results:

- The results for De Bilt are only statistically different from those for Lelystad for spacious sewer systems (small off);
- The results for Bordeaux, Plymouth en Porto are statistically different from those for Lelystad for all sewer systems;
- The results for Göteborg are statistically different from those for Lelystad for all but one sewer system;
- The results for Gdańsk and Stockholm are only statistically different from those for Lelystad for tight sewer systems;
- The results for Lisboa, Nantes en Southampton give a less clear picture; notably for the spacious systems the results are statistically different from those for Lelystad.

Especially for high values of the threshold, one should be careful to draw conclusions. In fact the considered length of the precipitation depth series is too short to be representative for the real probability distribution of the number of days with extremely high precipitation depth.

From figure 14 and figure 15 the following can be noted:

- Gdańsk en Stockholm are the only two stations with overflow frequencies predominantly smaller than for Lelystad;

- Porto results in extremely large overflow frequencies notably for the spacious sewer systems;
- Lelystad and De Bilt agree, as expected, very well.

The results for Gdańsk and Stockholm show a decrease in the overflow frequencies for almost all sewer systems. Because of the easterly location of those stations the climate has a more continental character, resulting in less extreme rainfall events.

The extremely large overflow frequencies for Porto can also be explained by the geographical location. Porto is located in front of a mountain range. Air flowing from the Atlantic Ocean in northeasterly direction is lifted up by the mountain range, causing orographic precipitation.

When, for a moment, De Bilt, Porto, Gdańsk and Stockholm are left out of consideration, an assessment can be made of the upper and lower boundaries of future changes in overflow frequency due to climate change. If the analysis is restricted to sewer systems for which the present $off > 7/\text{year}$ (figure 7), the lower boundary is given by the results for Lisboa, Nantes and Southampton (dependent on whether or not the results for those stations are statistically different from those for De Bilt). The upper boundary is given by the results for Plymouth. The lower boundary for off varies between a decrease of 15% to a decrease of 30%, and the upper boundary for off varies between an increase of 35% to and increase of 130%.

The margin between the upper and lower boundaries is rather large. Furthermore, the boundaries will vary according to the number of stations which are involved in the analysis. For the time being, however, the results give a reasonable impression of the boundaries within which the effects of climate change on off must be sought.

4 Summary and conclusions

In the present article the sensitivity of sewer systems to climate change has been studied using a reservoir model and an existing precipitation record of Lelystad (15 years of precipitation depth at 5 minute time intervals). Overflow variables were defined for the reservoir. The sensitivity of those variables to changes in the reservoir parameters and artificial transformations of the precipitation series were assessed using the reservoir model. The impact of climate change on the overflow frequency (off) was also assessed using the daily data of the analogous climates.

The following general conclusions can be drawn:

- For the purpose of assessing the impact of climate change, it is useless to construct more complicated sewer system models than the one presented in this article if there is no certainty on how a climate change will manifest itself in the short-term rainfall data;
- If at all possible, the climate modelers should provide much more detailed information about how future climate change will manifest itself in short-term precipitation records; it is not enough, e.g., to know that the annual increase in precipitation depth will be 20%, even knowing the monthly increase or decrease is not enough; it must be known whether an increase or decrease in precipitation depth will, e.g., cause more or fewer storms or whether the increase or decrease will be manifested by multiplication or by addition and subtraction of the original series, or a combination of these;
- The relative changes in the overflow variables are very sensitive to changes in the reservoir parameters; therefore, the impact of a future change in the precipitation series will be different for each sewer system;
- The overflow variables show a clear seasonal pattern with minima in the months of January, February, March, April, and December and maxima in the months of June, July, and August; therefore, it is important to know the exact seasonal pattern of a future climate change, because a seasonal pattern in a future climate change may change the values of the overflow variables considerably; e.g., the effect of a net annual increase in precipitation depth of 20% on the maximum annual overflow intensity may be greatly amplified by a seasonal pattern or may be nearly zero (see figure 12, cases 14 and 15);
- The method used for transforming an existing precipitation series to obtain an increase or decrease in precipitation depth, is extremely important as is illustrated in table 4;
- The daily analogous climate data can be used to calculate the changes in overflow frequency;
- The results for the analogous climate data give a reasonable upper and lower boundary; the lower boundary for off varies between a decrease

of 15% to a decrease of 30% and the upper boundary for *off* varies between an increase of 35% to and increase of 130%.

The most important conclusion which can be drawn here, is that a future climate change may have important consequences on the overflow frequencies and other overflowvariables of sewer systems and, therefore, on the receiving water-ecosystems. Since the life span of sewer systems and the time of occurrence of a climate change are of the same order of magnitude, it may be wise now to take into account the possible effects of climate change in the design of sewer systems.

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A Appendix

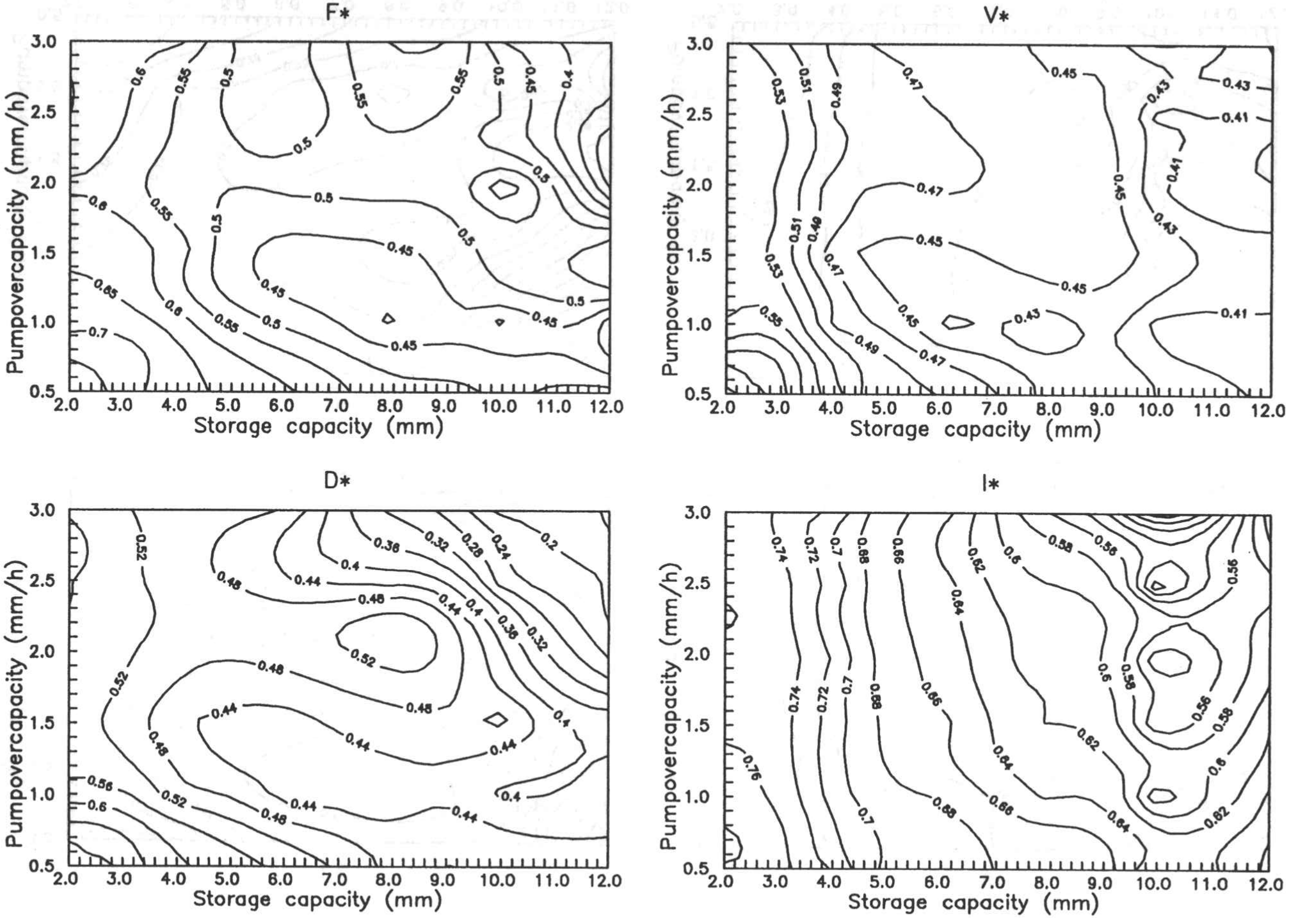

Figure 17: Results of case 1: $mpf = 0.8$.

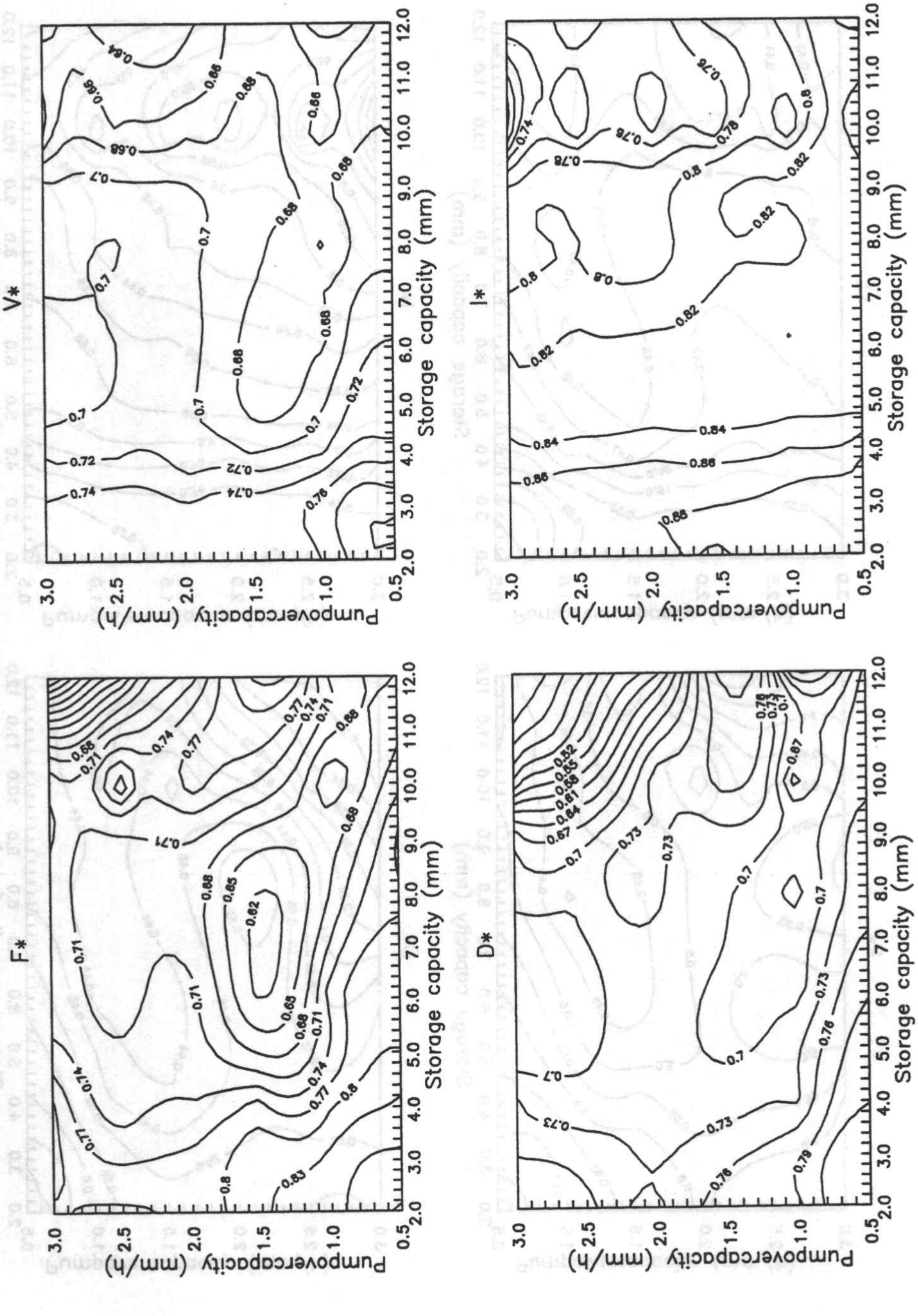

Figure 18: Results of case 2: $mpf = 0.9$.

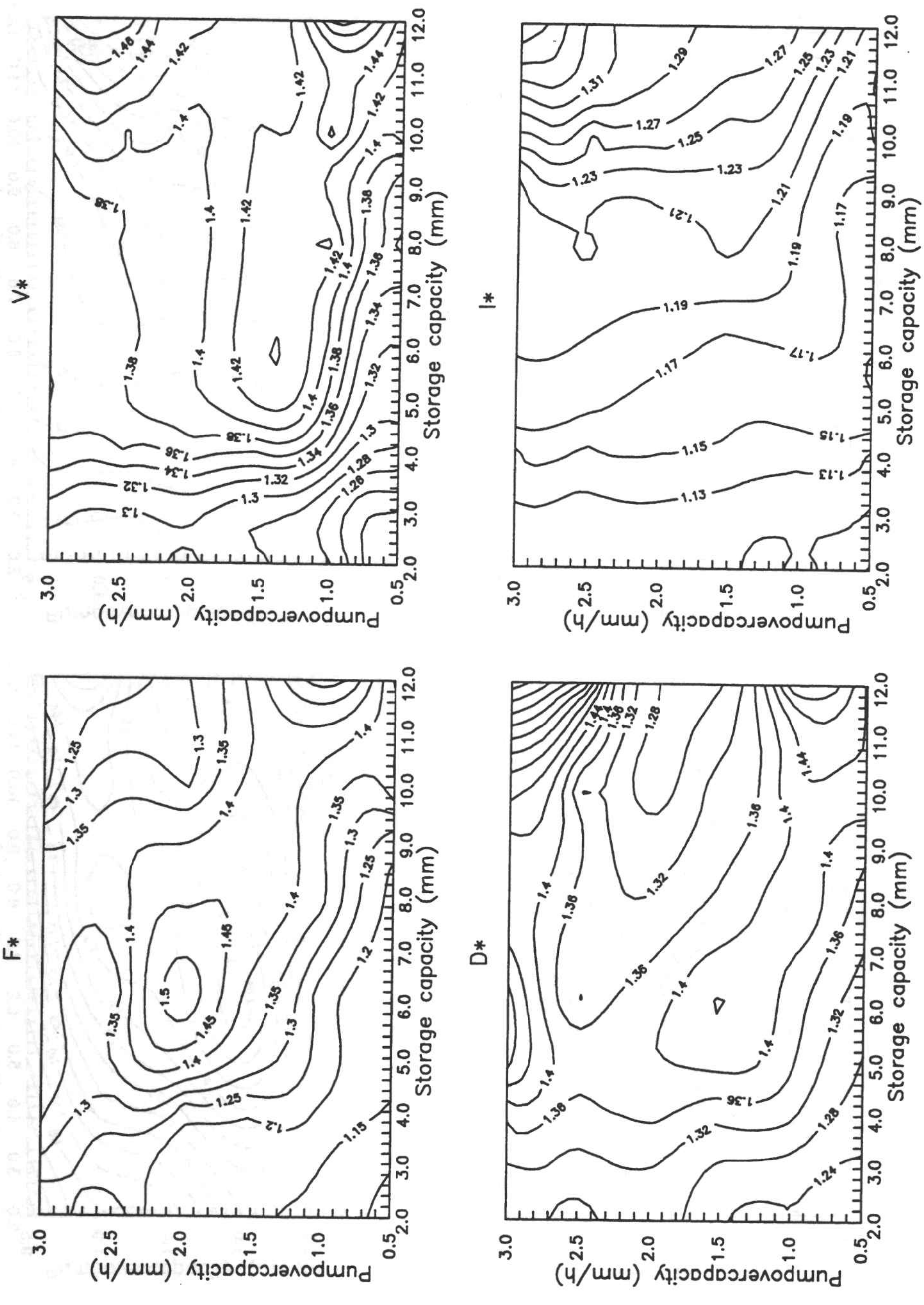

Figure 19: Results of case 3: $mpf = 1.1$.

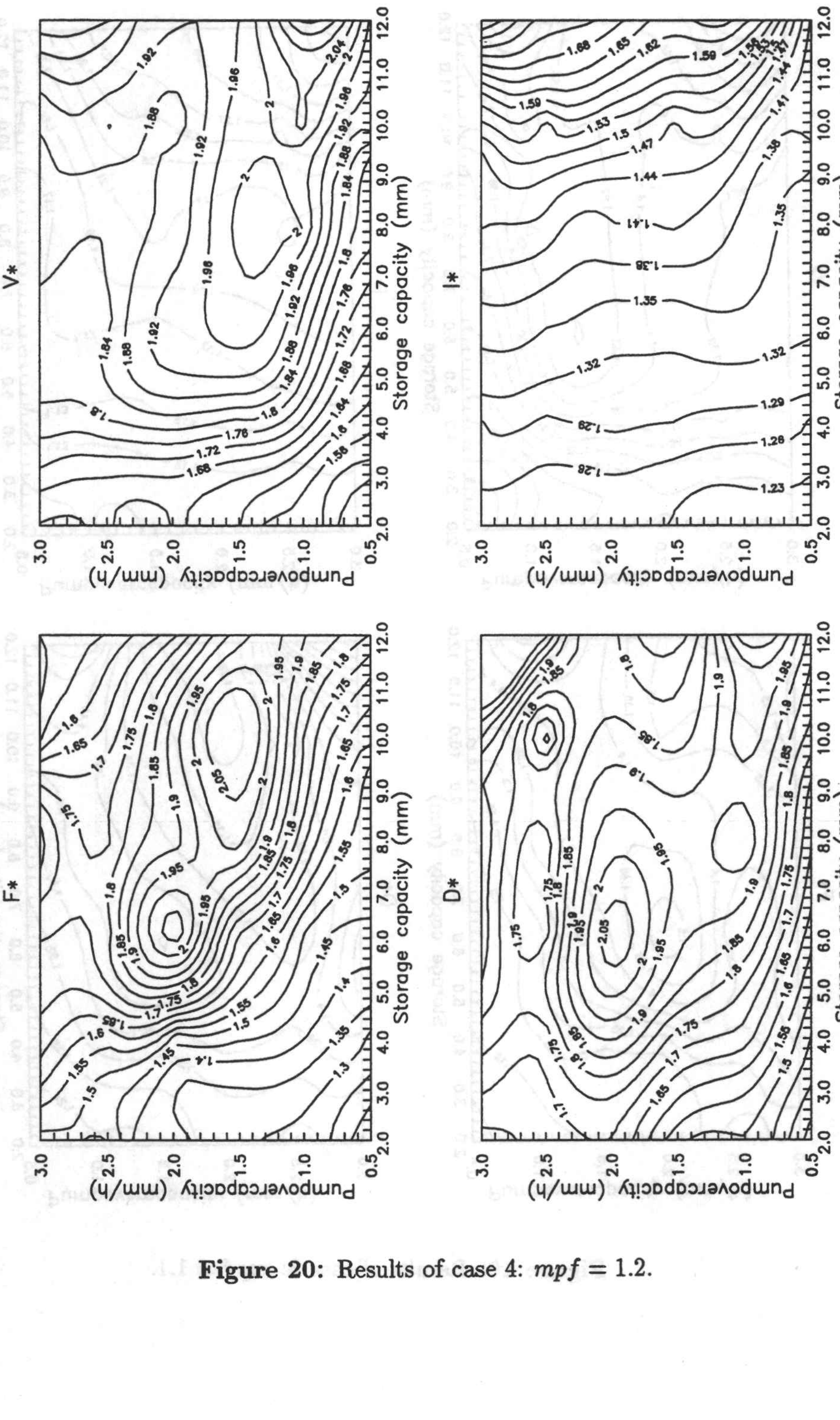

Figure 20: Results of case 4: $mpf = 1.2$.

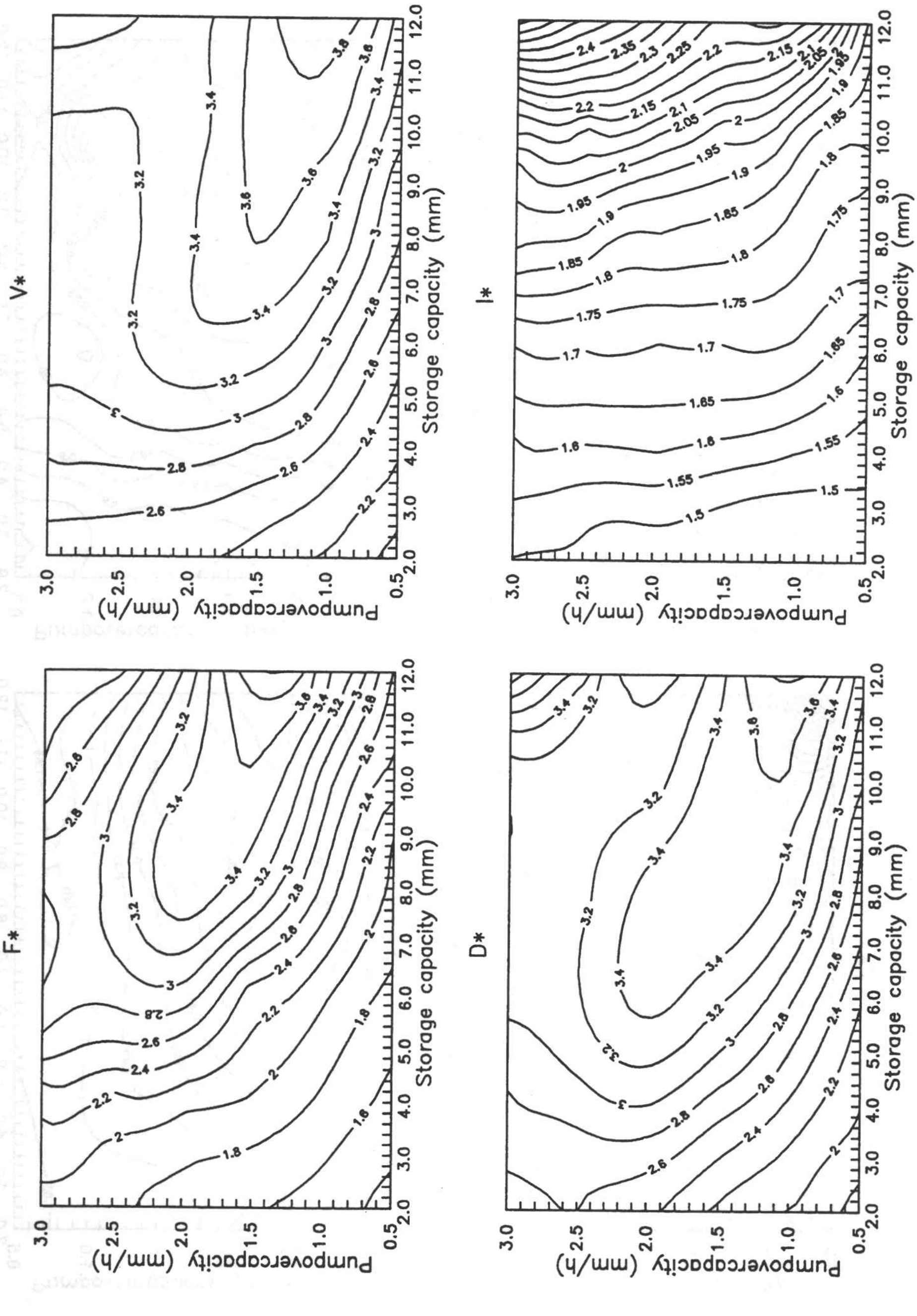

Figure 21: Results of case 5: $mpf = 1.4$.

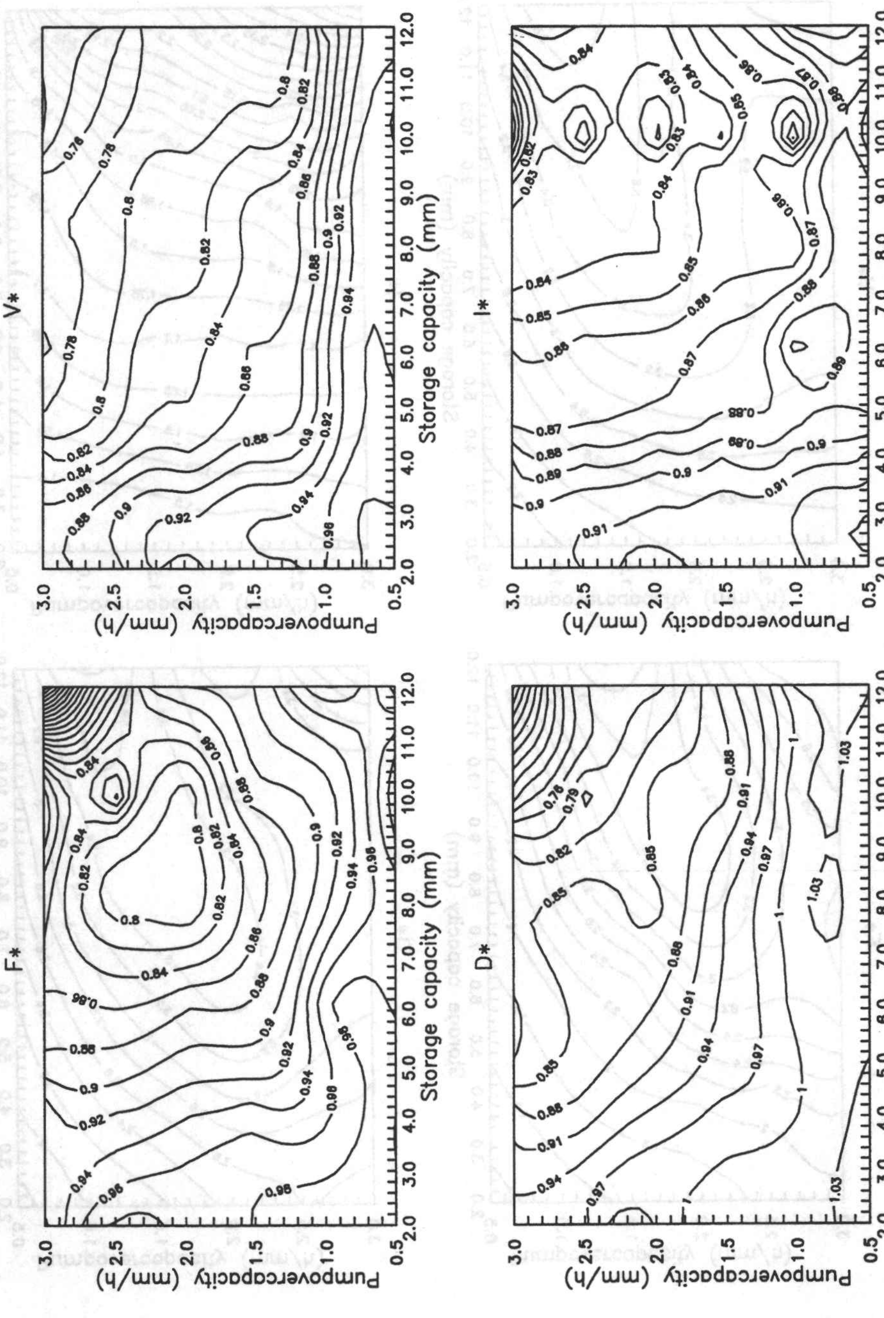

Figure 22: Results of case 6: $mpf = 1.0$, $b = 0.1$, and $\phi = 1/3\pi$.

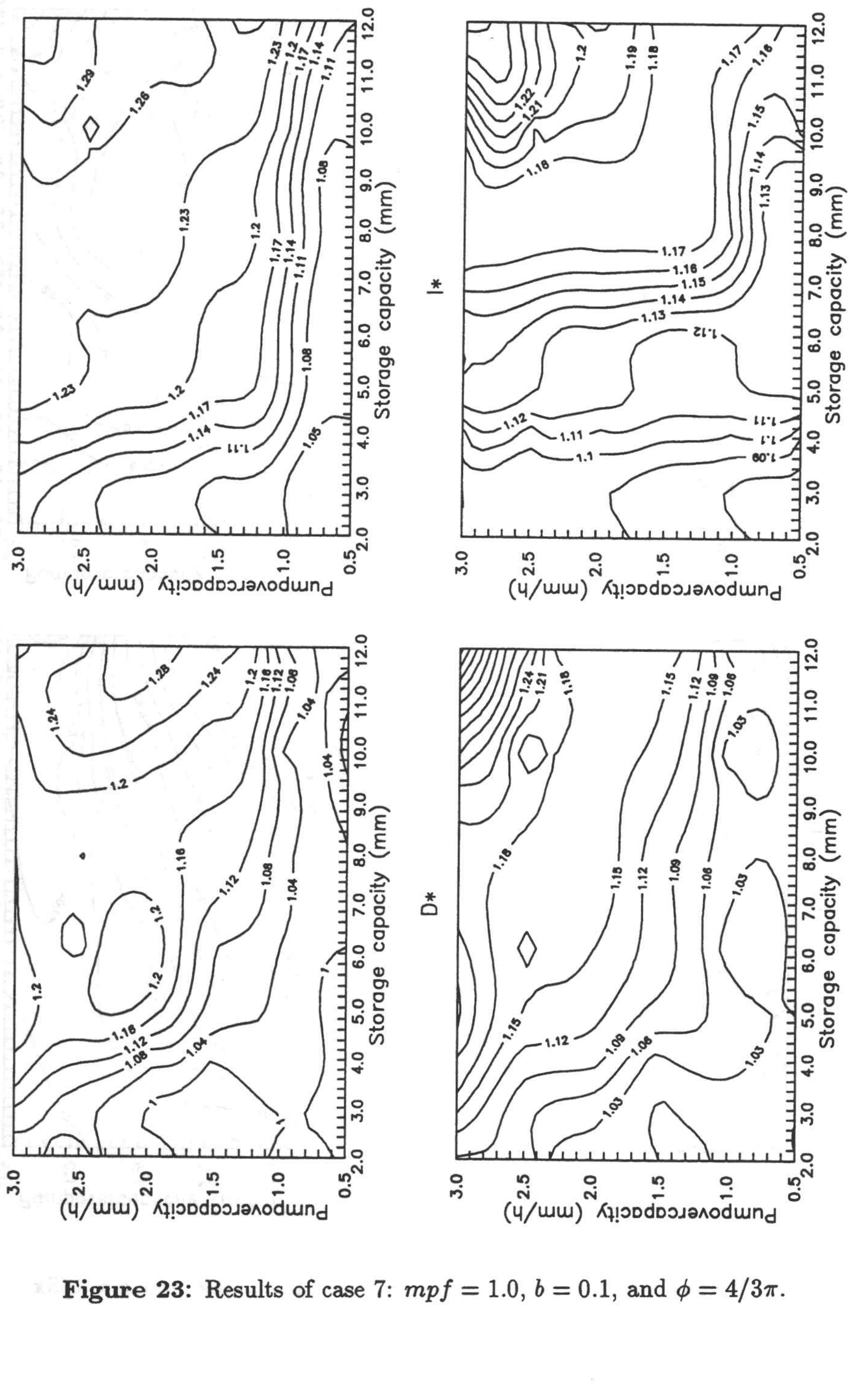

Figure 23: Results of case 7: $mpf = 1.0$, $b = 0.1$, and $\phi = 4/3\pi$.

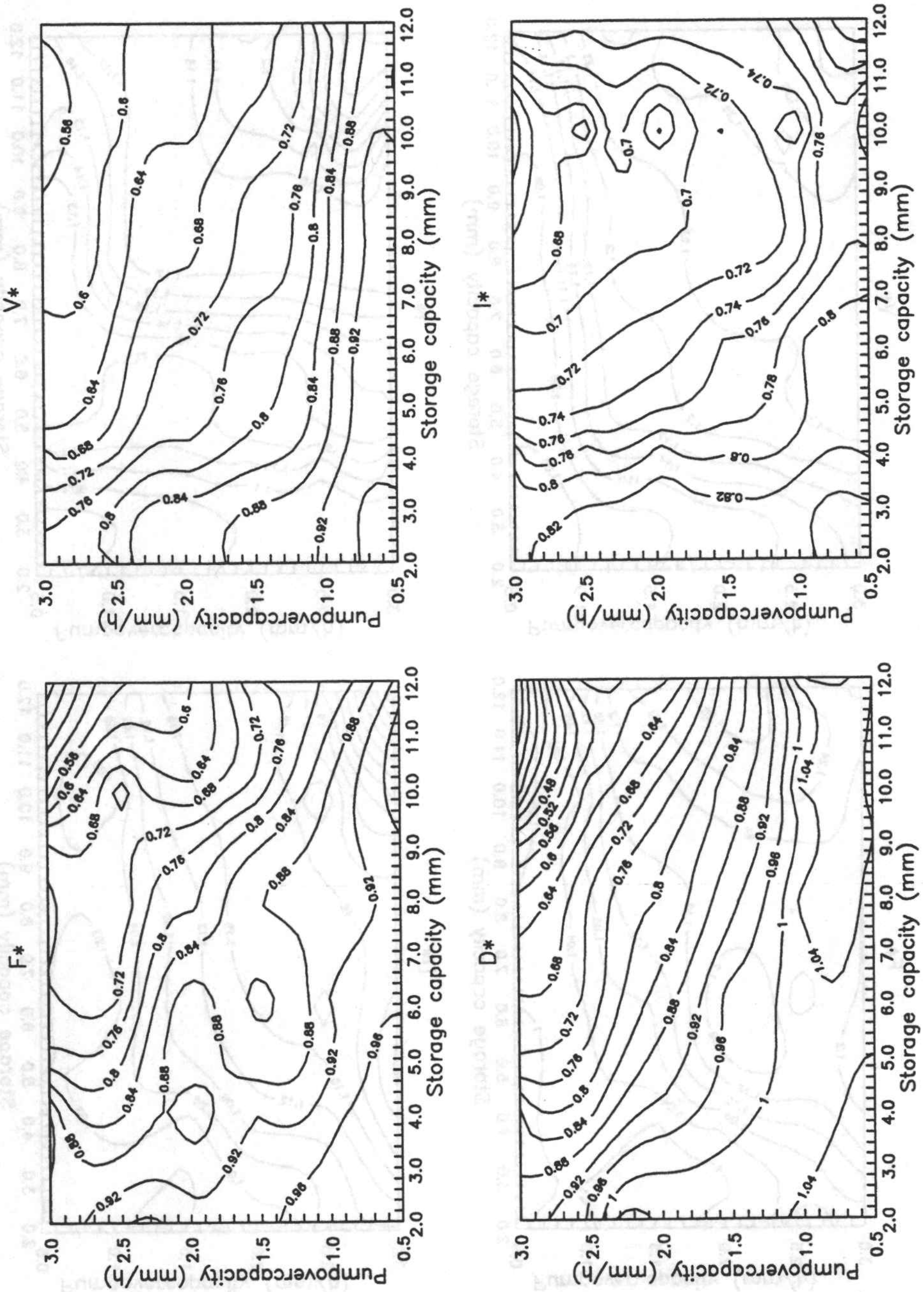

Figure 24: Results of case 8: $mpf = 1.0$, $b = 0.2$, and $\phi = 1/3\pi$.

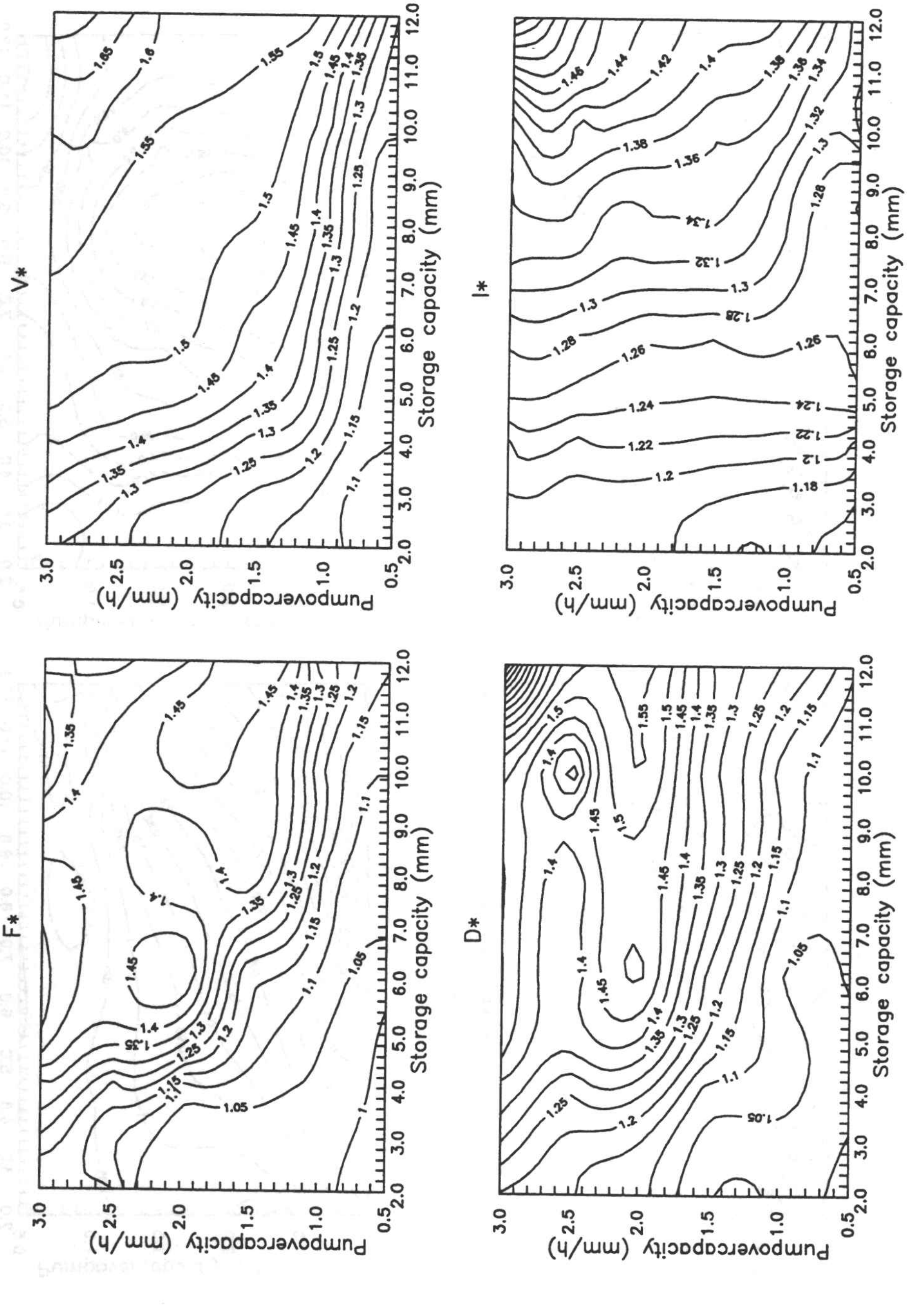

Figure 25: Results of case 9: $mpf = 1.0$, $b = 0.2$, and $\phi = 4/3\pi$.

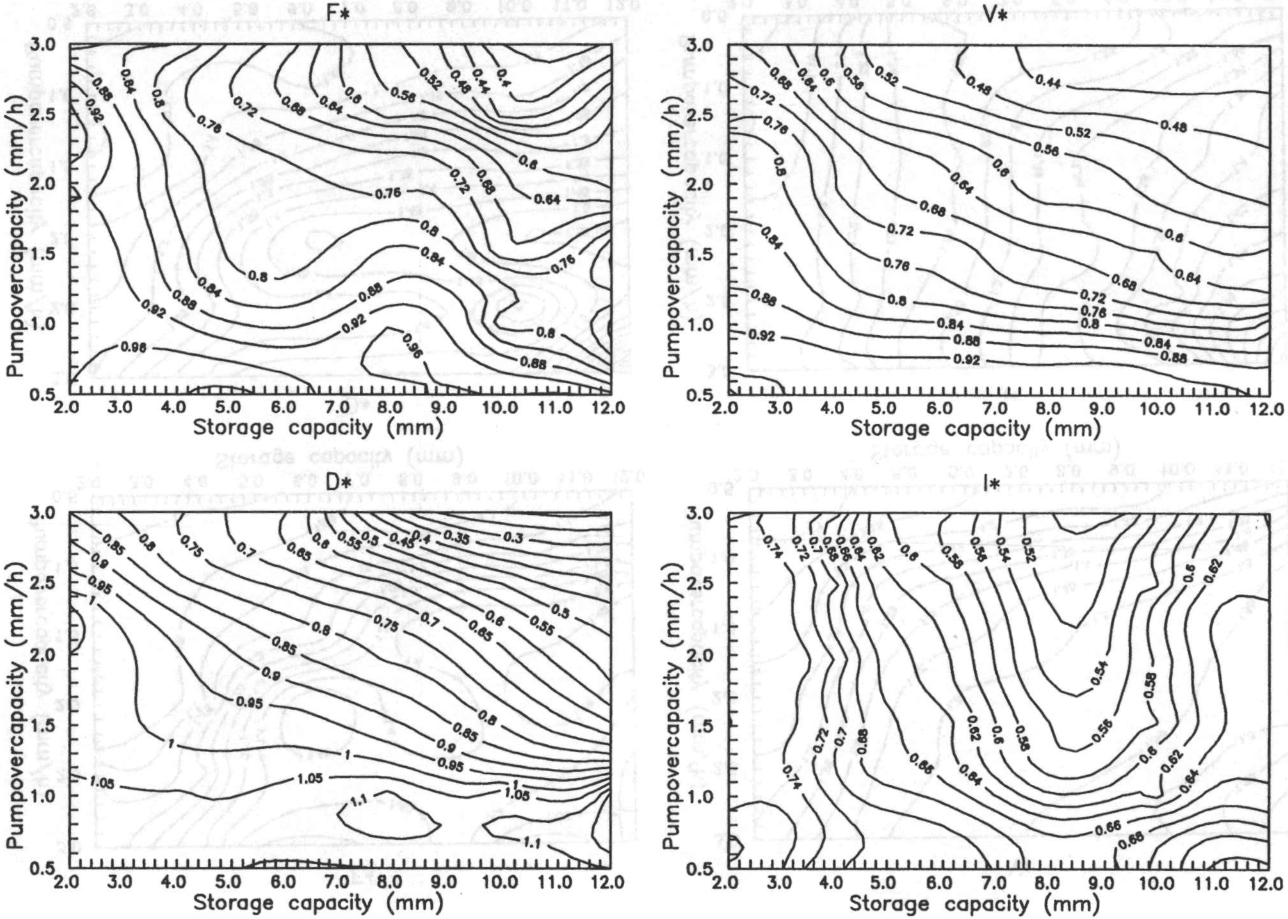

Figure 26: Results of case 10: $mpf = 1.0$, $b = 0.3$, and $\phi = 1/3\pi$.

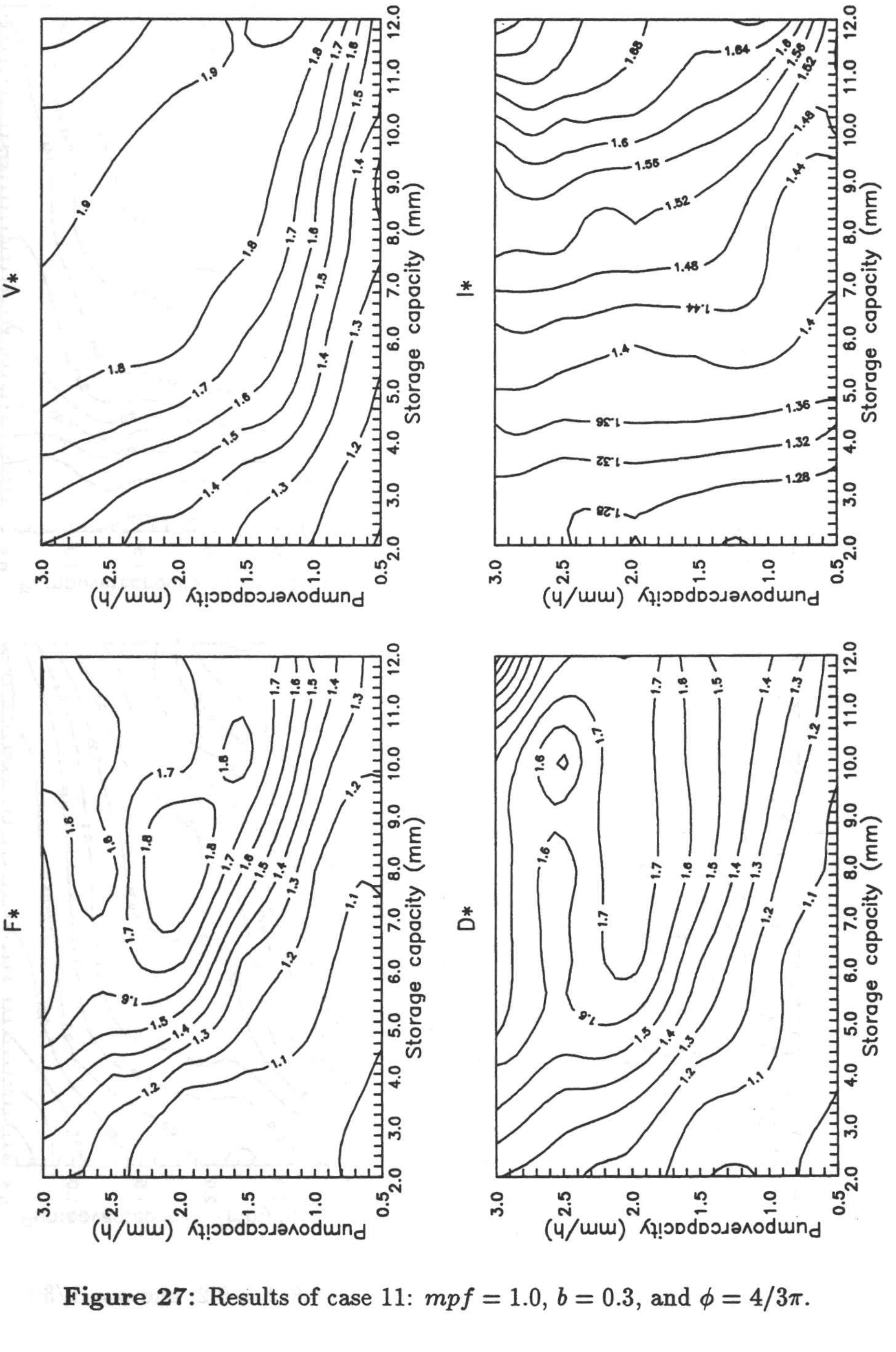

Figure 27: Results of case 11: $mpf = 1.0$, $b = 0.3$, and $\phi = 4/3\pi$.

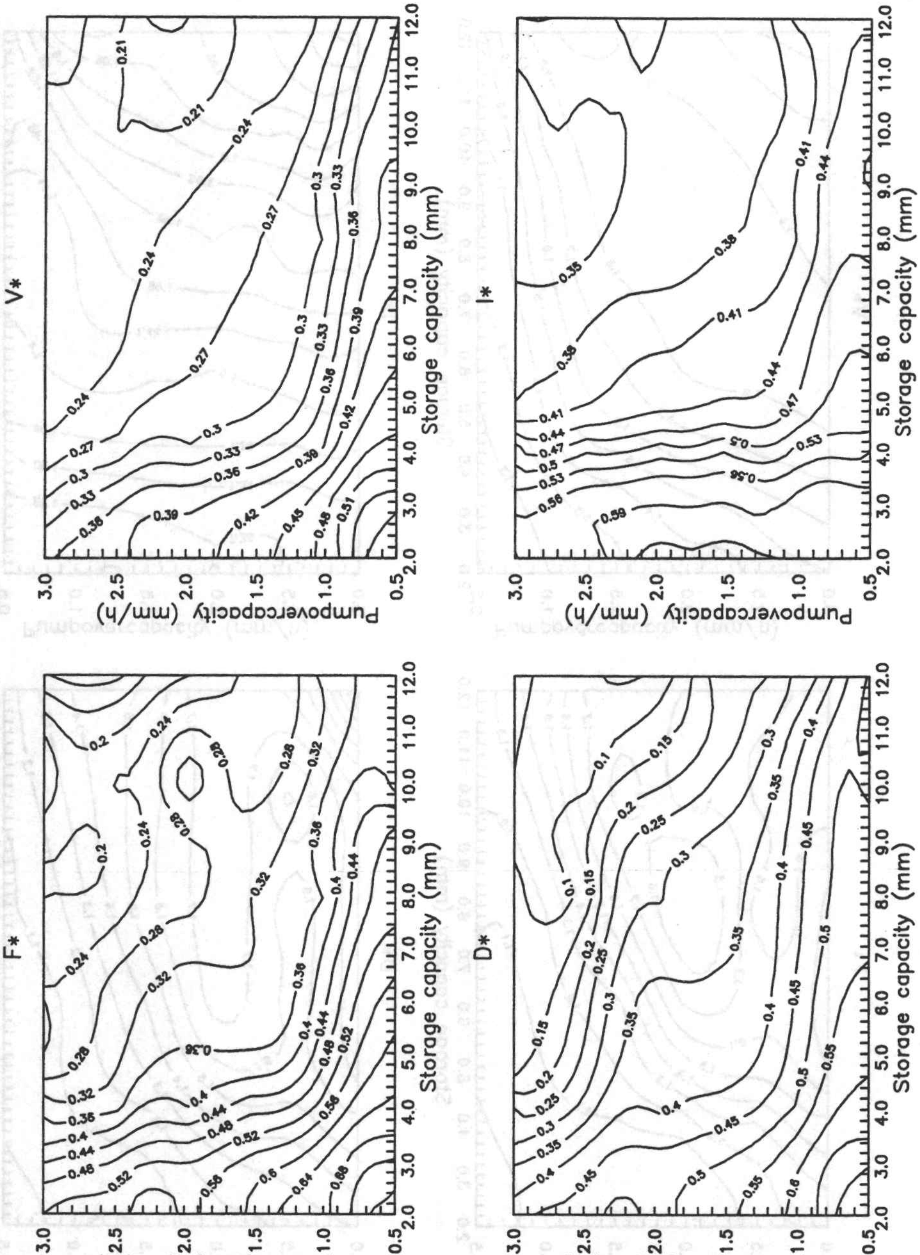

Figure 28: Results of case 12: $mpf = 0.8$, $b = 0.2$, and $\phi = 1/3\pi$.

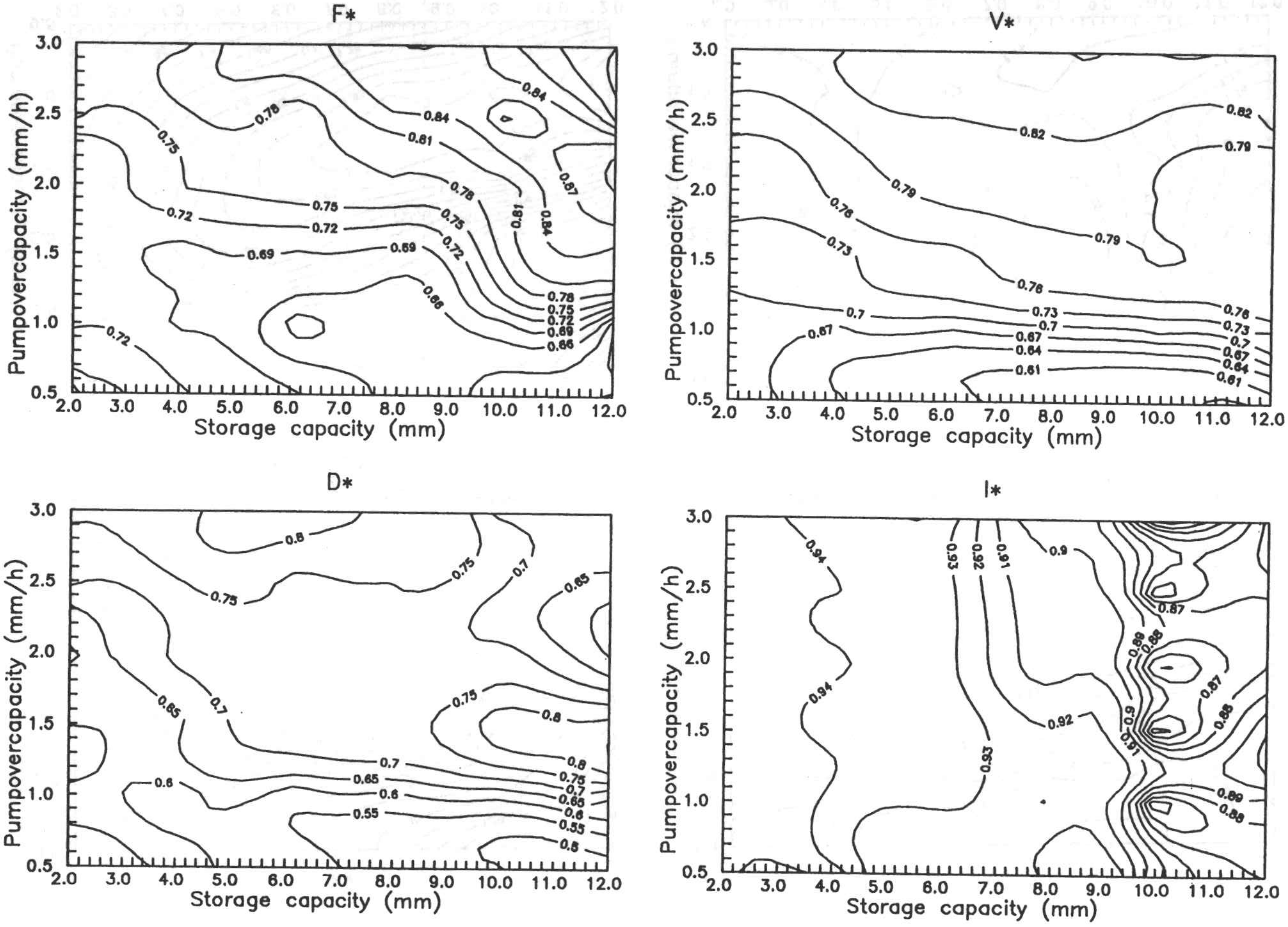

Figure 29: Results of case 13: $mpf = 0.8$, $b = 0.2$, and $\phi = 4/3\pi$.

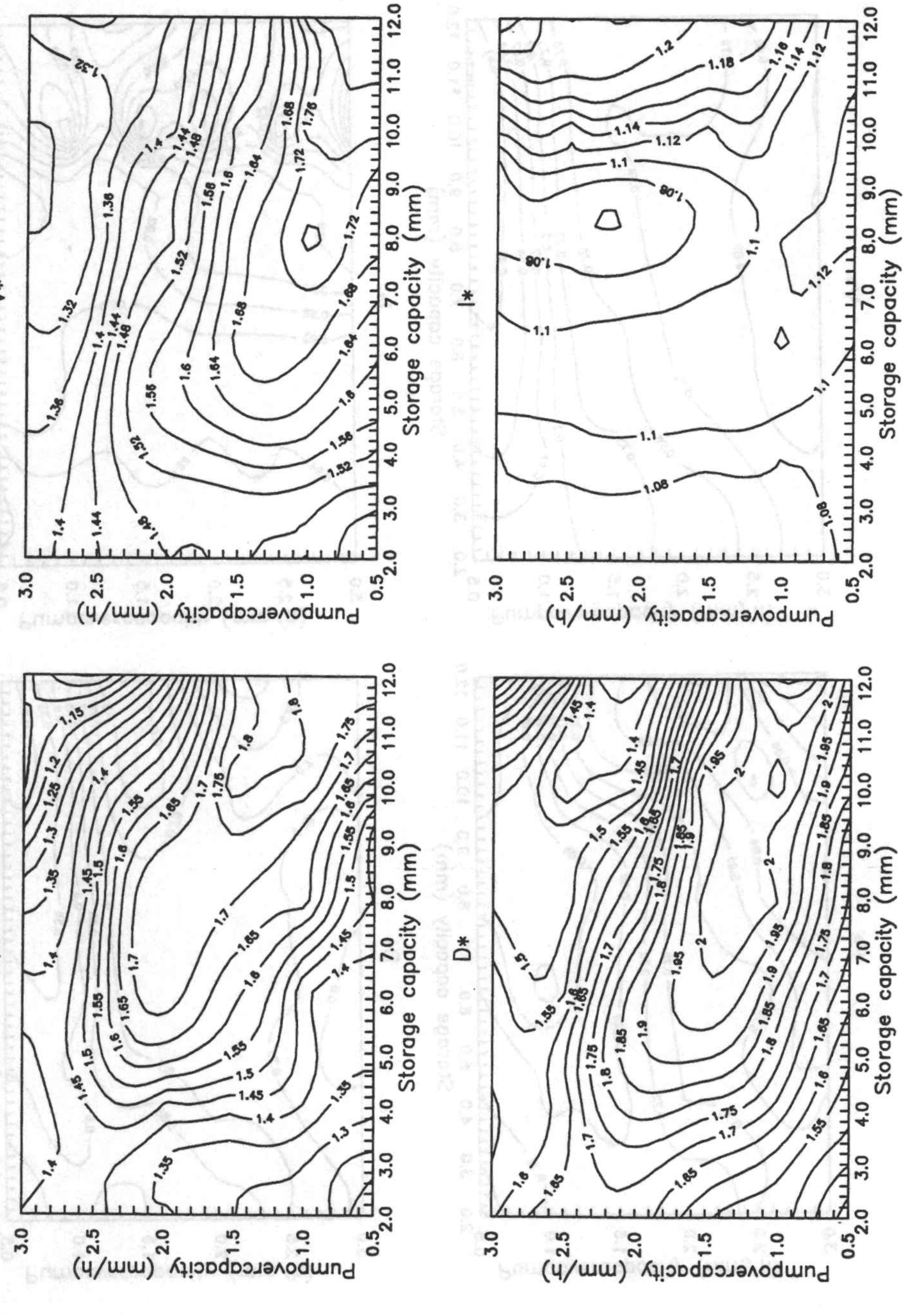

Figure 30: Results of case 14: $mpf = 1.2$, $b = 0.2$, and $\phi = 1/3\pi$.

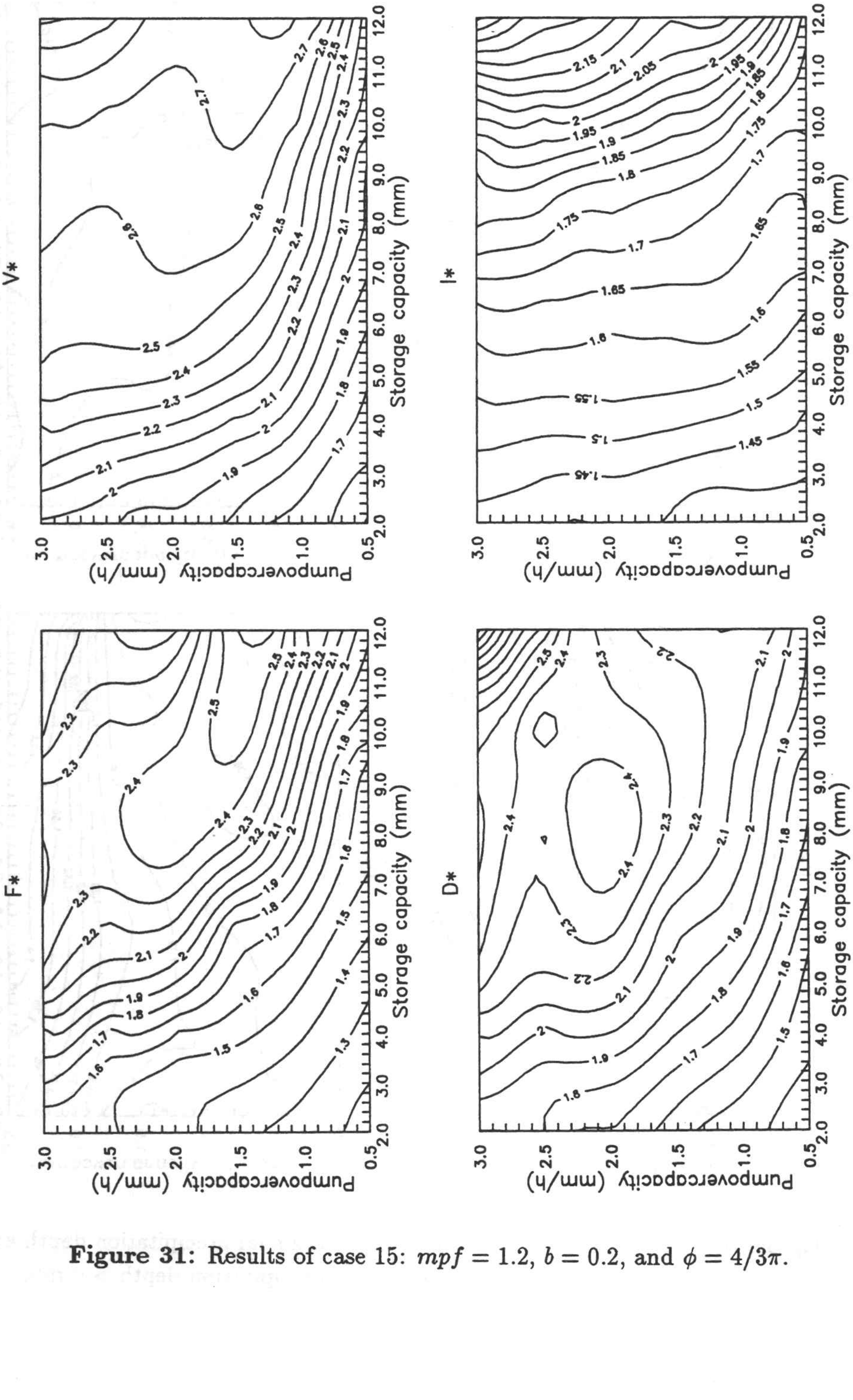

Figure 31: Results of case 15: $mpf = 1.2$, $b = 0.2$, and $\phi = 4/3\pi$.

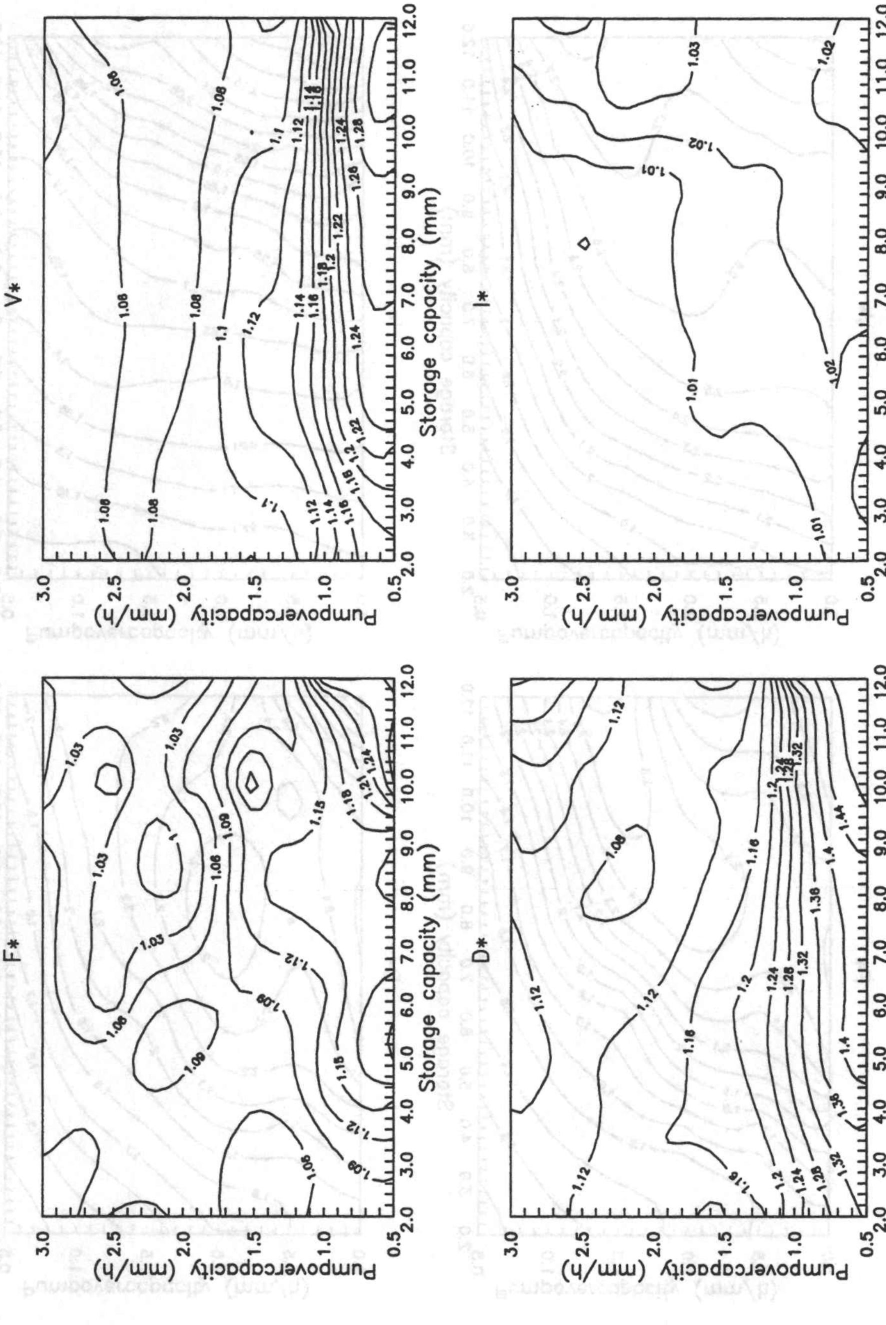

Figure 32: Results of case 16: 20% increase in annual precipitation depth equally distributed across all 5-minutes intervals with precipitation depth > 0 mm.

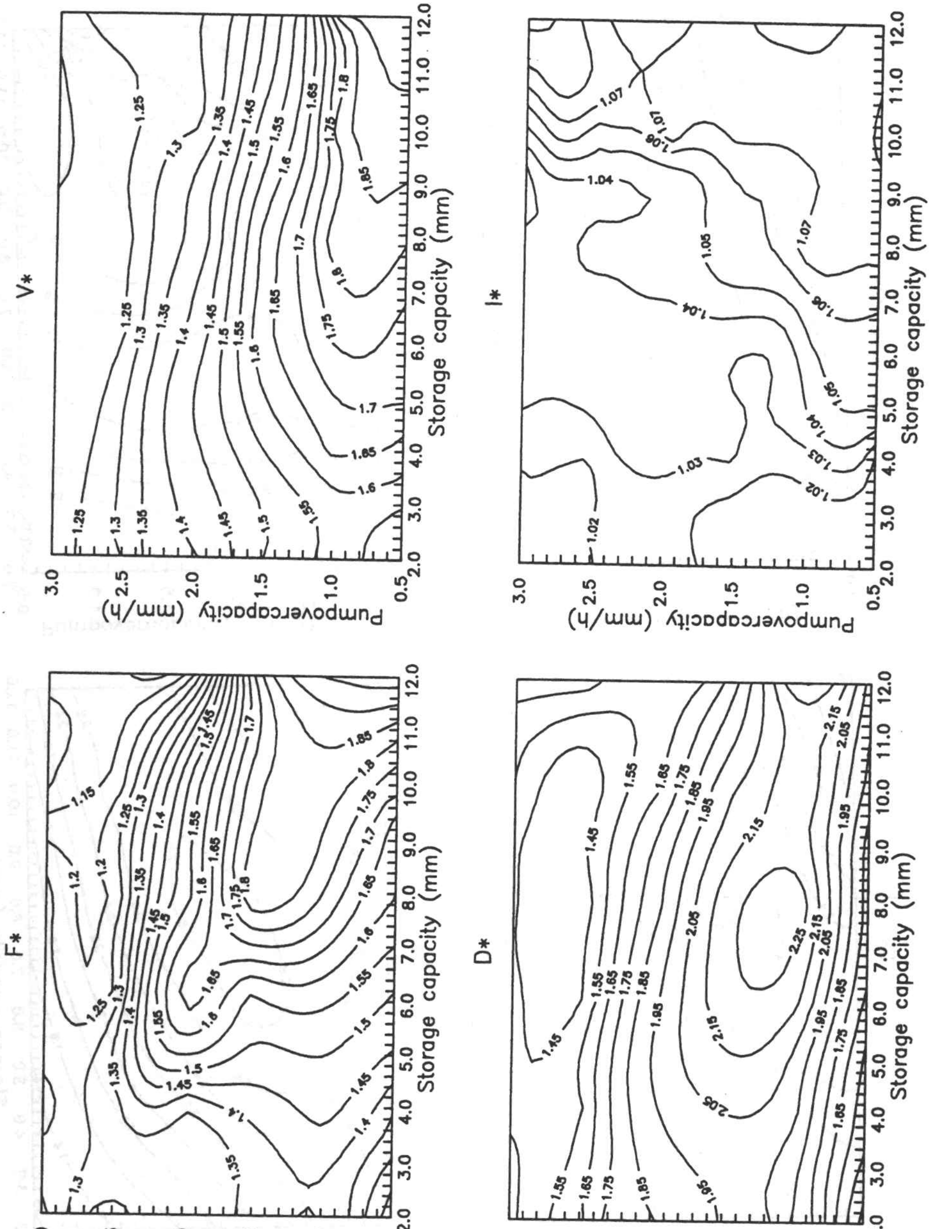

Figure 33: Results of case 17: 20% increase in annual precipitation depth equally distributed across all 5-minutes intervals with precipitation depth > 0.05 mm.

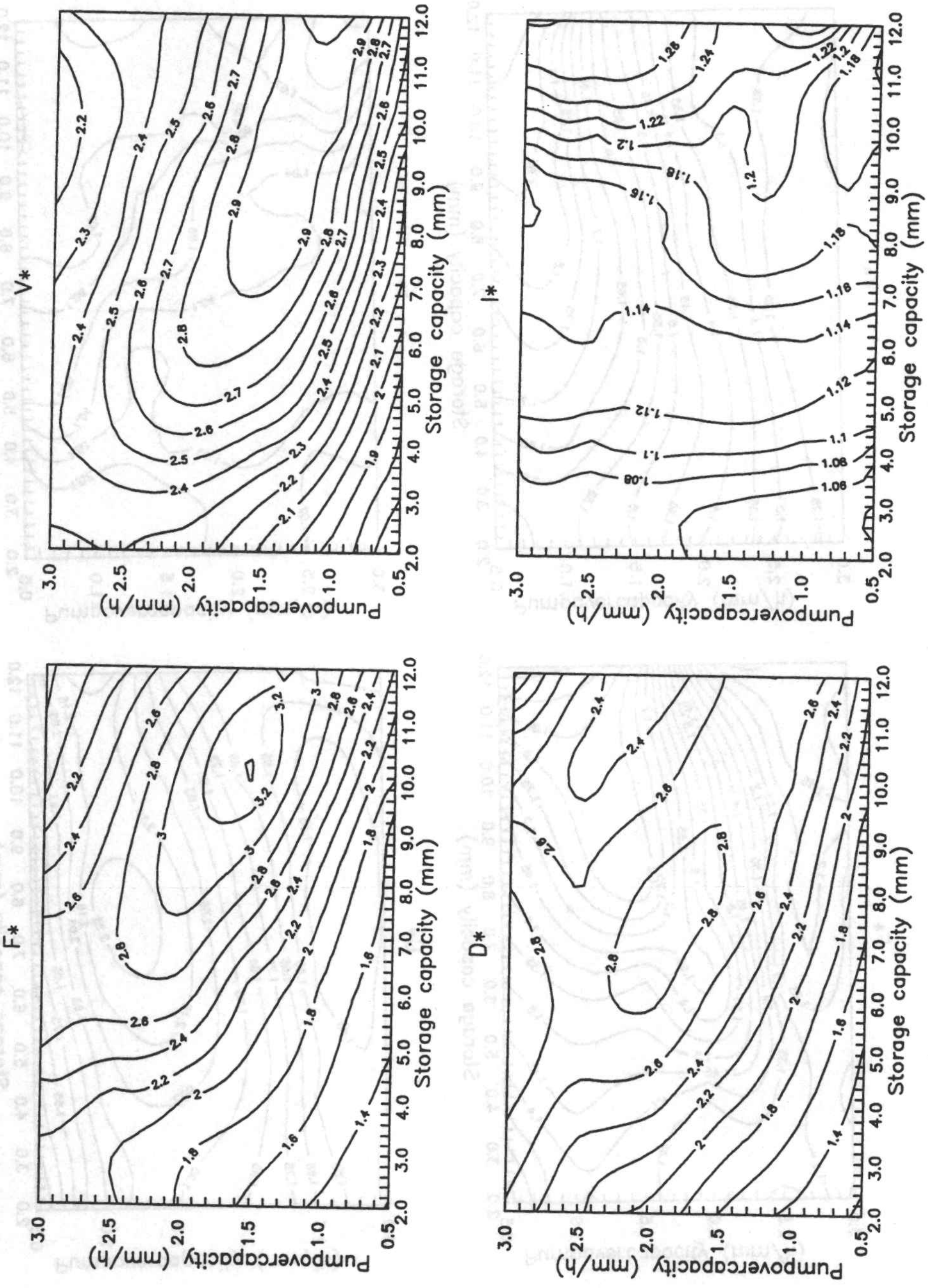

Figure 34: Results of case 18: 20% increase in annual precipitation depth equally distributed across all 5-minutes intervals with precipitation depth > 0.2 mm.

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