Design optimization of drinking water filtration plants

Use of filtration models and micro-computers

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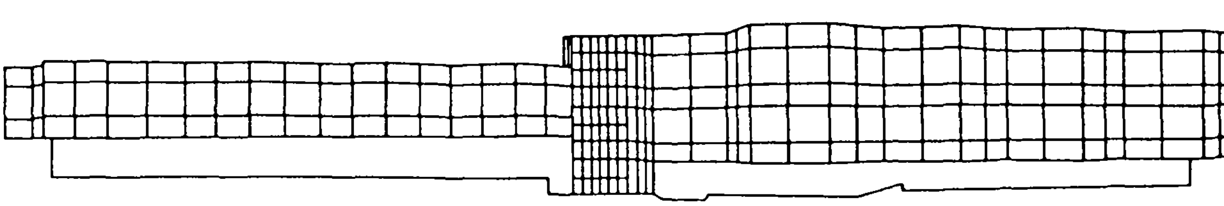

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DESIGN OPTIMIZATION OF DRINKING WATER FILTRATION PLANTS : USE OF FILTRATION MODELS AND MICRO-COMPUTERS.

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ABSTRACT

Filtration models can be a valuable tool for the design engineer in the evaluation of such alternatives as filtration rate, bed height and grain size. Based on a survey of field plants, it is shown that the model of Lerk-Maroudas can simulate fairly well the development of head loss and quality improvement during a filter run.
A simulation programme is presented that enables rapid assessment of the effect of alternatives.
The programme can be executed on a programmable pocket-calculator (such as HP-41 CV) or on a microcomputer (such as IBM-PC) and is illustrated by the example of the new drinking water filtration plant Temghar for the city of Bombay (capacity 2.88 m^3/s).
In order to determine a proper value for the parameters that represent the floc size and composition, a separate calibration programme was made.
With this programme field measurements-e.g. of a pilot-filter- can be used to calibrate the filtration model, i.e. to determine the most reliable input data for the simulation programme.

1. INTRODUCTION

The designer of a drinking water filtration plant faces the task of finding the optimum process conditions. This includes the selection of:

- the type of filter:
  upflow or downflow
  single layer or duble layer
  gravity or pressure
  wet or dry
- the bed composition:
  grain material, size,
  porosity and bed height
- the filtration rate
- the allowable head loss
- the length of the filter run

in such a way that with a given influent quality the desired effluent quality is guaranteed.
In many cases pilot-plant experiments are carried out in order to select between the design alternatives. In view of the numerous alternatives, the experimental procedure can be quite lengthy and laborious. Consequently a filtration model that can simulate the effect of design alternatives and thus limit the amount of experimental work will be a valuable tool to the design engineer.
Such a model should simulate properly the processes of a rapid filter and in particular the development of head loss and quality improvement during a filter run.
In this paper we will present a filtration model that fulfills these requirements. We will demonstrate the use of microcomputers to execute the calculations and provide clear graphs of the results.
The use of the programme will be illustrated by the example of the new drinking water filtration plant Temghar for the city of Bombay (cap. 2.88 m^3/s) which is presently under construction.

2. PROBLEMS WITH FILTRATION MODELS

Many investigators have studied the theory and application of filtration models [1]. The result is an almost as great amount of filtration models, which differ from each other in minor or major ways.
Morever application of the models is complicated by the following constraints:

- Many models are so intricate that the necessary calculations can only be executed by complex computer programme on large mainframe computers
- All models contain several parameters and coefficients that can only be found through a calibration procedure.

As a result of both constraints, the model is often regarded a "black box". The design engineer cannot interprete the results properly, especially since the calibration of the model is done by "trial and error". The consequence is that the model is put aside and that one will work on the basis of common sense and information of comparable filtration plants.

In order to be an effective tool to the design engineer, a model should include the main design parameters for filtration but allow for relatively simple calculation procedures. Moreover, there should be a limited number of calibration coëfficients in the model. It is regarded that the Lerk-Maroudas model complies with these requirements.

3. FILTRATION MODEL ACCORDING TO LERK-MAROUDAS

The model is based on the following considerations.

The initial removal of suspended matter follows a first-order relationship with the filterbed height, whereas the filtration coëfficient is a function of grain size, filtration rate and viscosity.

During the filter run, suspended matter is accumulated in the bed resulting in a decreasing porosity. The accumulation can only proceed until the pores are filled to a maximum fraction as the velocity in the remaining pores will be so high that the flocs are broken and carried away. Consequently the filtration coefficient decreases proportionally with the remaining pore fraction.
The clean bed head loss is calculated with the equation of Carmen-Kozeney for laminar flow. During filtration the head loss increases as the remaining pore fraction decreases and the velocity in the remaining pores increases.

In the appendix the mathematical equations representing the model are given. The differential equations can be solved to obtain 2 solutions for effluent quality (equation 3) and head loss (equation 7). In these formulas some parameters are known from the design:

- d hydraulic diameter of filter grains
- p_o porosity of clean filterbed
- y, L depth of filterbed
- v filtration rate
- T filter run length
- H , allowable head loss over filter

Furthermore, some parameters representing the influent and effluent quality can easily be measured in practice:

- c_o influent concentration
- c_e effluent concentration
- T_e temperature

Finally some parameters representing the floc properties (density, strength, filtrability) can only be determined by calibration:

- *rho* *mass density of solids*
- n maximum fraction of pore filling
- m multiplying factor labda0

*The latter parameter represents the fil*trability of the solid particles and is used to correct the value of labda0 according to Lerk.

4. APPLICATION OF THE MODEL: SIMULATION OF FILTER PERFORMANCE

With the and of programmable pocket-calculators (such as HP 41-CV) and microcomputers (such as IBM-PC) it is relatively easy to execute the necessary calculations of the filtration model according to Lerk-Maroudas. The micro-computer has the big advantage of graphical presentation of the results.
Especially spreadsheet programmes such as Lotus 1.2.3, Symphony or Framework provide an easy way to obtain graphs that allow the designer to assess the impact of changes in design parameters in an easy, clear and comprehensive way.

We will demonstrate the use of a programme in Lotus 1, 2, 3, by the example of the new drinking water filtration plant of Temghar at Bombay, India (capacity 2.88 m^3/s). The design of this plant includes 16 filters of 80 m^2 and is shown in figure 1.
During the fair season, direct filtration of river Ulhas water is applied at a maximum filtration rate of 9.3 m/h.
During the monsoon season, the water first passes the clarifiers and the maximum filtration rate is reduced to 7.7 m/h. Both situations will be simulated with the programme.
The programme starts by asking the input data:

		Fair season	Monsoon season
1. hydraulic diameter of grains	[mm]?	0.9	0.9
2. porosity of clean filterbed	[%]?	42	42
3. maximum fraction of pore filling	[%]?	70	80
4. depth of filterbed	[m]?	1.1	1.1
5. water temperature	[°C]?	25	25
6. filtration rate	[m/h]?	9.3	7.7
7. influent concentration	[mg/l]?	5 as SS	2 as Al
8. mass density of solids	[kg/m³]?	25	3
9. multiplying factor labda0	[dim less]?	1	1
10 depth of supernatant water	[m]?	1.3	1.3
11 filterrun length	[m]?	80	80
12 interval of output results	[h]?	4	4

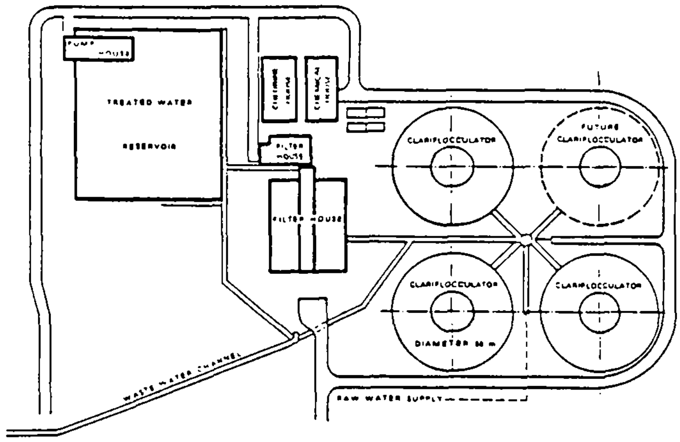
It is noted that the parameters 1,2,4,5,6,7 and 10 are known from the design. The data 3, 8 and 9 should be obtained from the calibration of the model, as will be explained in the next paragraph.
The data 11 and 12 are used only to determine the format of the output.

After the input is completed, the programme executes the calculations within seconds. The results are presented either as a table or as graphs.
Figures 2 and 3 give the graphical results of the abovementioned input data.
From the effluent quality graphs, it can be seen that the effluent quality deteriorates much faster in the monsoon season than in the fair season.
The acceptable run length is 46 hours in the monsoon season (criterion c_e = 0.15 mg/l Al) and more than 80 hours in the fair season (criterion c_e = 0.5 mg/lSS)

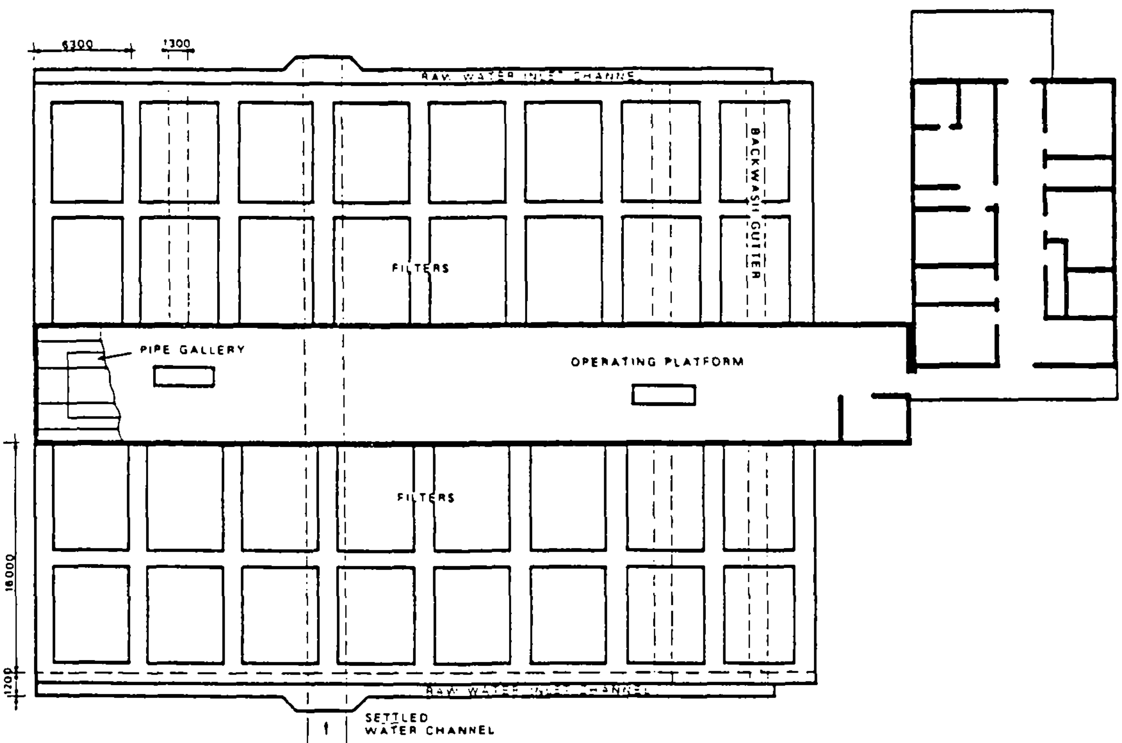
The head loss graph shows that head loss development is also much more rapid in the monsoon season. The maximum design head loss of 1.75 m is reached after 44 hours in the monsoon season, while in the fair season the allowable run length exceeds 80 hours.
The distribution of suspended solids shows a good deep bed filtration in the fair season, whereas in the monsoon season surface filtration occurs.

DESIGN OF TREATMENT PLANT TEMGHAR

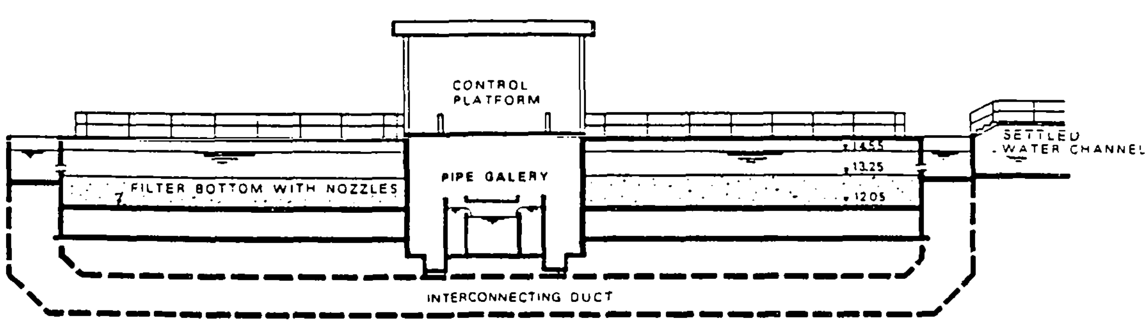
FIGURE 1



PLANT LAYOUT



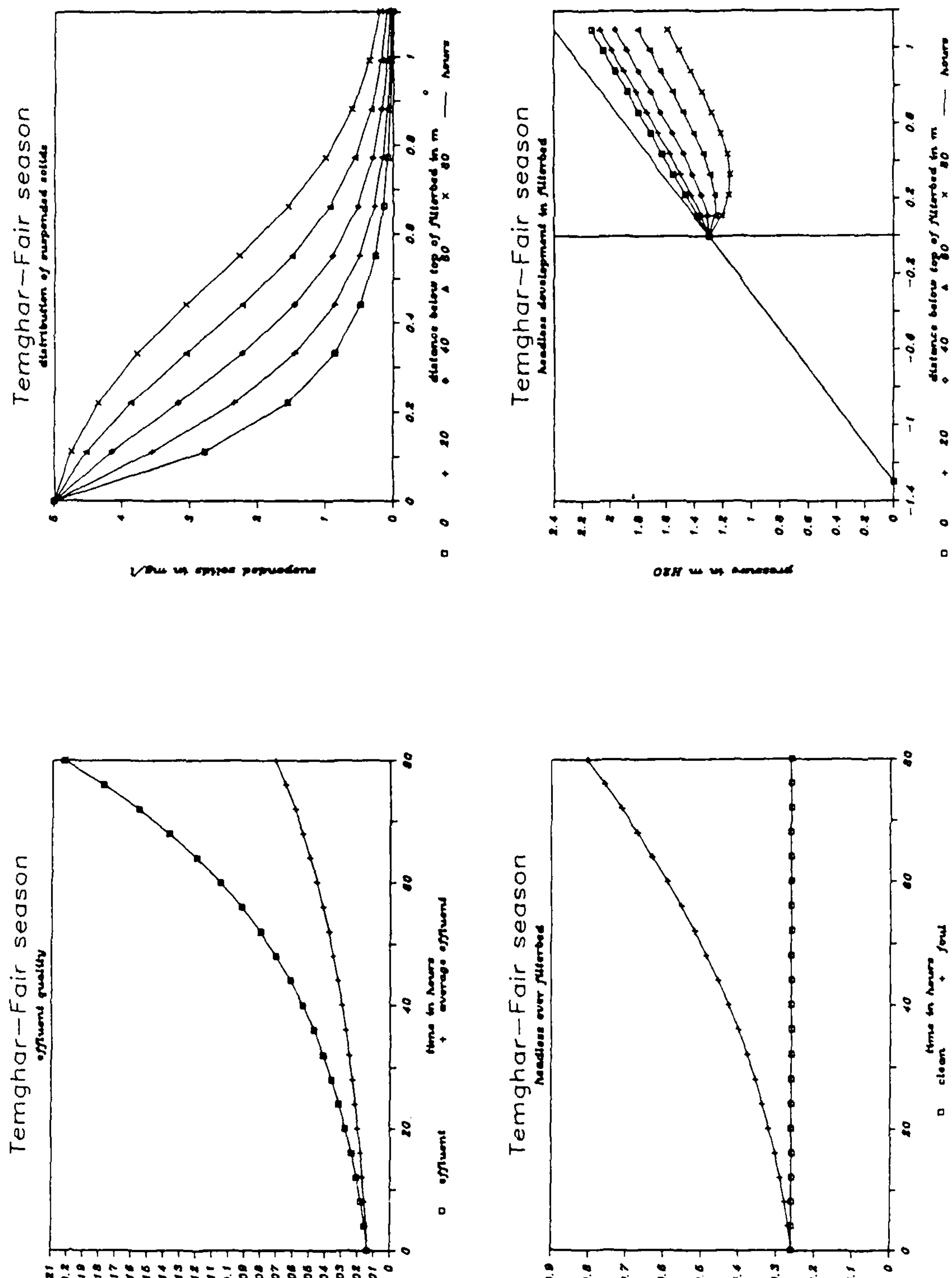
LAYOUT FILTER HOUSE



SECTION OF FILTERS

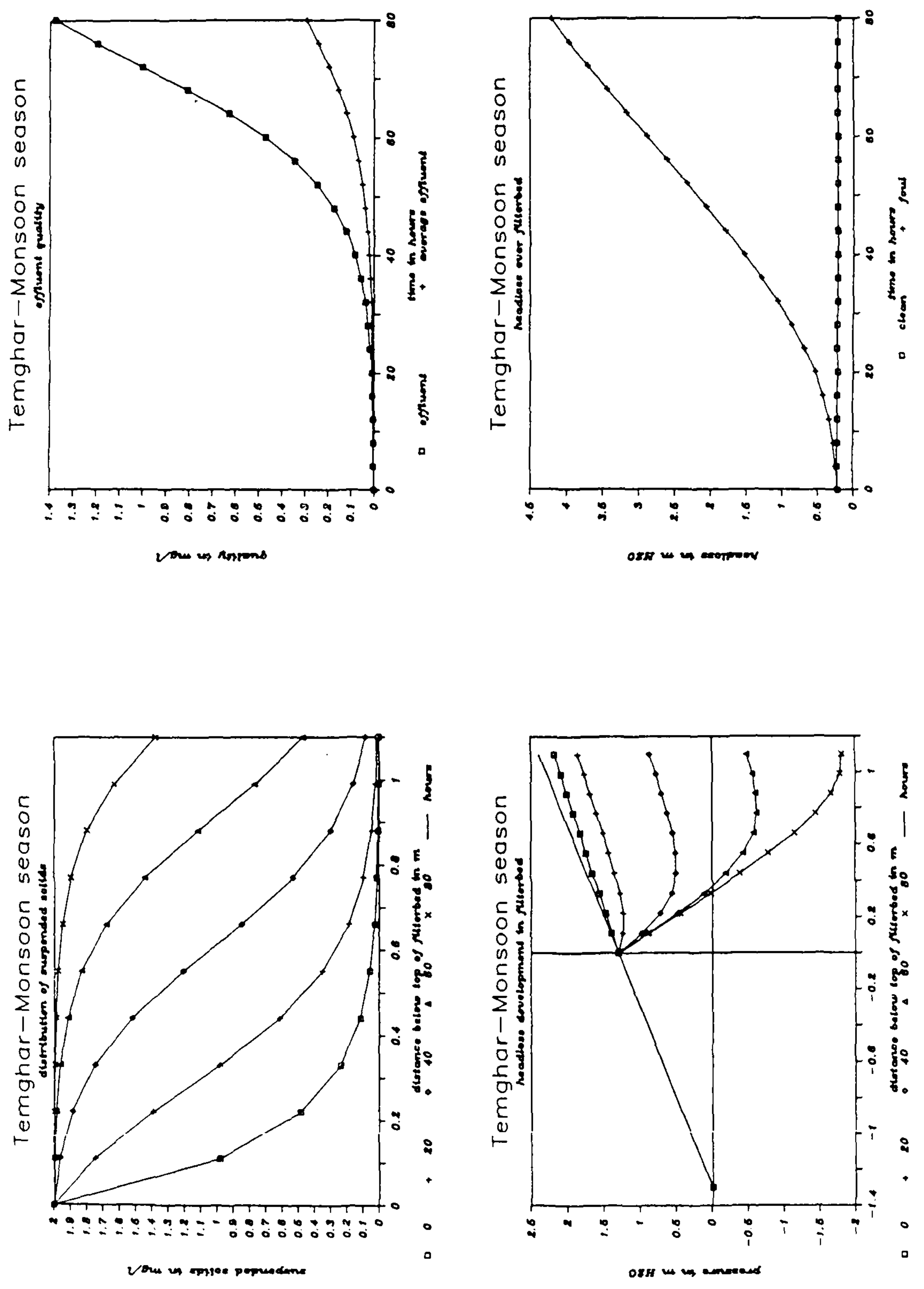
FIGURE 2

MODEL RESULTS TEMGHAR, FAIR SEASON



MODEL RESULTS TEMGHAR, MONSOON SEASON

FIGURE 3



Particularly interesting is the graph which gives the hydrostatic and remaining pressures over the filterbed height. This is the equivalent of the well known Lundquest-graph and the occurence of negative pressure in the filterbed can be observed from it.
It is noted that during the monson season negative pressures occur after some 50 hours.
It will be clear that the programme is excellently suited to evaluate the effect of changes in design or operating conditions. Vary rapidly the designer can see the effect of such changes as:

- bed composition : grain size, porosity, bed height
- influent load : influent concentration and temperature
- filtration rate
- filterrun length

on the effluent quality and head loss development.
It is noted that the reliability of the results depends largely on the accuracy of the parameters representing floc density, strength and filtrability, i.e. rho, n and m. This will be discussed in the next paragraph.

5. CALIBRATION OF THE MODEL: CALCULATIONS AND SENSITIVELY ANALYSIS

The parameters representing floc density, strength and filtrability - i.e. rho, n an m - cannot be measured in practice, but have to be obtained through calibration of the model by pilot-plant or field measurements. A problem is that the analytical solution of the model gives explicit formulas for c and H (formulas 3 and 7 in appendix I), but not for rho, n and m. These parameters have to determined by trial and error or through structured iteration. Consequently, a separate calibration programme was prepared, based on the following considerations:

1. A starting value for m is assumed, usually 1.

2. For any given value of m and consequently labda0, combinations or rho and n can be calculated for which the model output for effluent quality and head loss equals the measured values.
   This is done by the regula falsi iteration method using starting values for n_{min}, n_{max}, rho_{min} and rho_{max} as indicated in figure 4.
   The correct combination or rho and n for the given m-value is found where both lines intersect.

3. Once a solution is found for rho and n, the same procedure can be repeated for another value of m and consequently labda0.
   Thus it is possible to compute combinations of m, rho and n that match the actual results.

It is noted that all 3 parameters have a large influence on the model output, as discussed below.

- rho: the impact of rho on effluent quality will be relatively big, expecially near the end of the filter run, as can be seen from equation 3. Calculations show that an increase in rho leads to a more than proportional decrease of c_e. With regard to head loss, an increase of rho leads to a proportional decrease as is demonstrated by model calculations
- n: the impact n on effluent quality is the same as with rho. However the effect on head loss is much higher, especially near the end of the filter run when the head loss is proprotional to $(1 - \frac{1}{n})^2$.
- m: the impact of m on effluent quality is rather big; an increase in m leads to a decrease in c_e. The impact on head loss is less marked.

For the model input data of Temghar (monsoon season), a sensitivity analysis was made of the effect of a 10% increase or decrease of the calibration parameters on the model output. The results presented in table 1 confirm the above mentioned relationships.

Table 1: Influence of calibrations parameters on model output

		rho		n		m	
	initial values	-10%	+10%	-10%	+10%	-10%	+10%
rho	3	2.7	3.3				
n	80			72	88		
m	1					0.9	1.1
calculation results (T= 44 hours)							
c_e (g/m^3)	0.12	0.19	0.08	0.19	0.08	0.16	0.09
H_e (m H_2O)	1.75	2.12	1.53	1.30	2.89	1.65	1.92
percentage change							
c_e		58	34	58	34	33	25
H_e		21	13	26	65	6	10

6. SURVEY OF FIELD PLANT RESULTS AND MODEL CALCULATIONS

A survey was performed of existing treatment plants in the Netherlands and abroad to study the applicability of the model to simulate filter performances [2, 3]. The survey included a total of approximately 10 surface water treatment plants and 20

FIGURE 4

CALCULATION OF RHO AND N

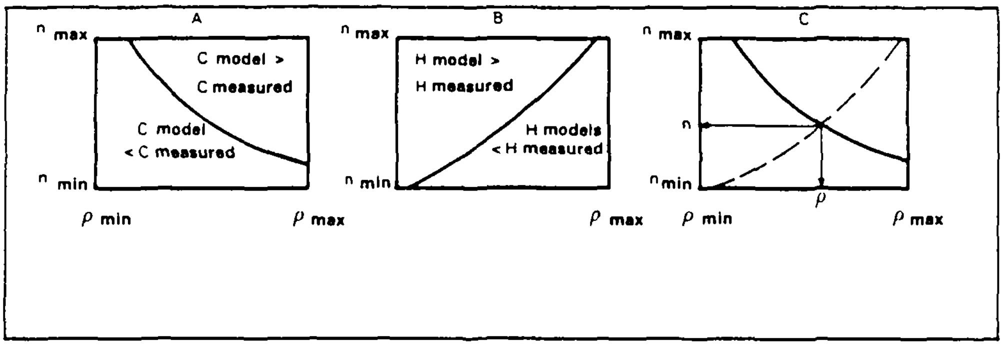
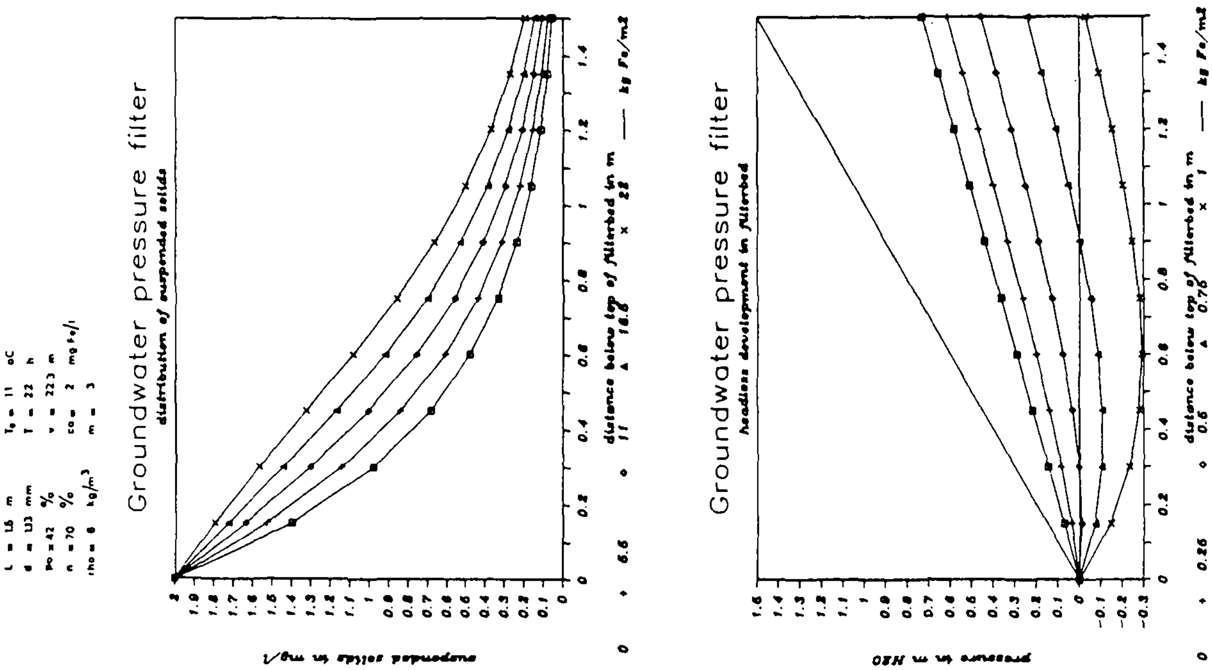


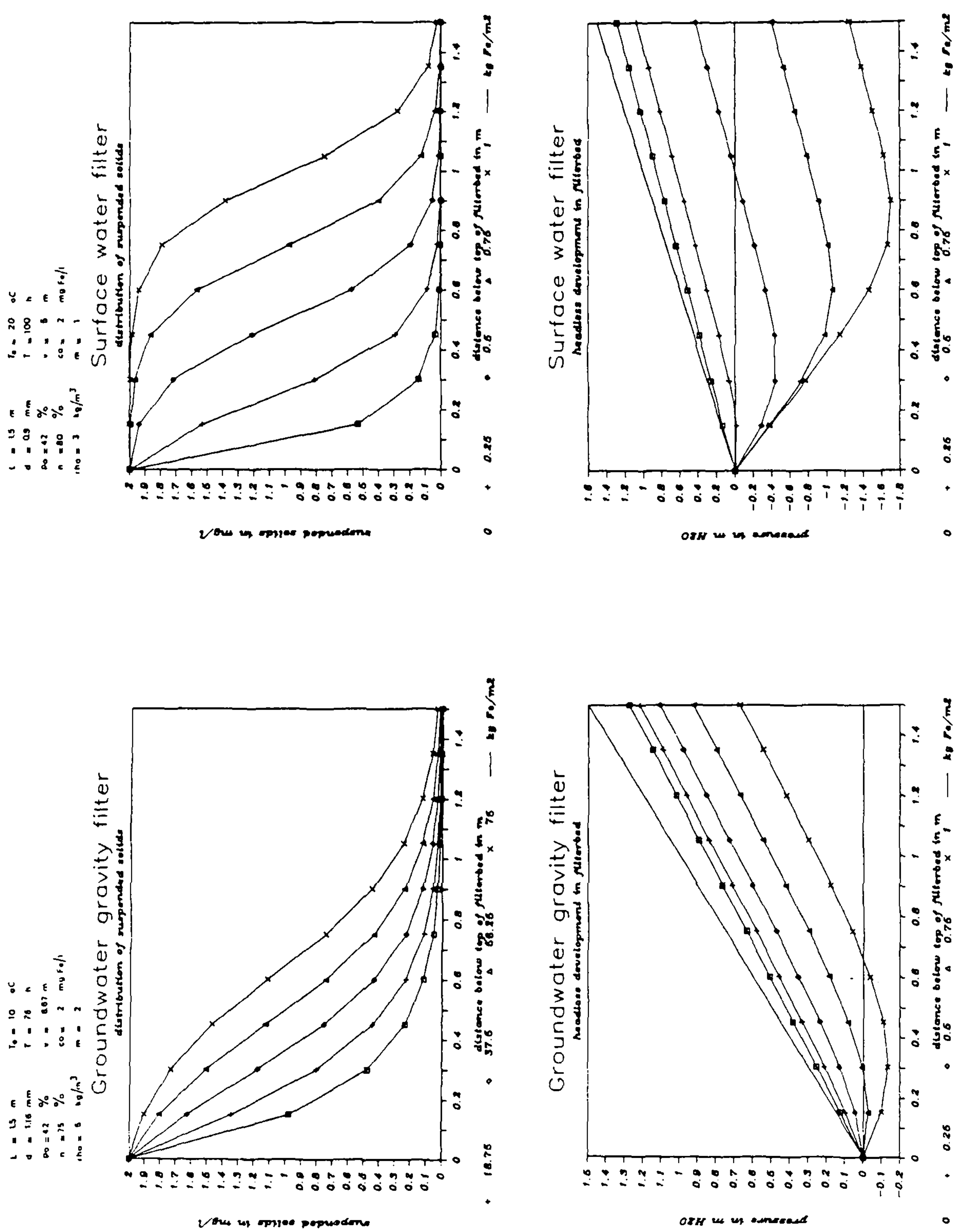
FIGURE 5[a]

MODEL RESULTS FOR DIFFERENT TREATMENT SYSTEMS



MODEL RESULTS FOR DIFFERENT TREATMENT SYSTEMS

FIGURE 5b



groundwater treatment plants. It was concluded that significant differences occurred between apparently comparable filter plants, so the results of the model should be interpreted with caution.
However, it appeared that the calibration parameters of table 2 generally lead to reasonable results.

Table 2: Results of field survey

	rho	n	m
direct filtration of surface water	25-40	70	1
filtration of surface water after sedimentation	15-25	70	1
filtration after flocculation with Fe, Al	3-4	80	1
filtration after flocculation with poly electrolyte	0.5-1	90	1
ground water filtration (Fe) by gravity	6	75	2
ground water filtration (Fe) pressure	5	70	3

It is noted that the influent quality is expressed in g/m^3 Fe or Al, except in the first two cases where g/m^3 SS is used.

It will be clear that table 2 can serve only as a guideline for the first estimate of model parameters and that pilot-plant tests remain indispensable as a basis for the calibration of the model and the design of any major plant. However the results from the field survey do improve insight in the mechanisms of filtration as illustrated by figure 5.

In this figure, the model output is presented for 3 essentially differing treatment plants, i.e. gravity filtration of surface water after coagulation, gravity filtration of groundwater and pressure filtration of groundwater (for iron removal).
The filterrun length was adjusted in such a way that the dry solids load at the end of the filter run is equal for all systems.
Looking at figure 5 some striking differences between the systems emerge. Though these differences were already known, they now get a certain theoretical support.
The surface water plant filters completely formed coagulation flocks. The raw water used has already had a primary treatment.
With filtration of aerated groundwater however, the forming of flocks for an important part will take place in the filterbed. The filter grains have a catalytical effect on this process.
Therefore deposition of dry solids will take place over a large part of the filterbed, in contrast to the surface water filter, where straining is the more important factor.
These differences are cleary visible in the graphs for the distribution of suspended solids in the filterbed. The slope of the lines for the surface water filter do not differ for the various dry solids loads.
This means that deposition of dry solids in a certain part of the filterbed take place untill a maximum value is reached.
Then the process is moved to a lower part of the filterbed.
In the graph for the groundwater filters the slopes of the dry solids distribution do change.
This means that deposition of solids still takes place over all of the filterbed. A distinct shifting of the frontdepth to lower parts of the filterbed is not present in the pressure filter.
The above also gives some explanation for the differences in the m, rho and n values for the 3 systems:

- rho: Because the iron flocks of the surface water plant are well formed at the start of filtration, a spacicous flock is formed. With the flock being formed in the filterbed when filtering groundwater, a more compact form is generated.
- n: Because of the deep bed filtration with groundwater the head loss development is less than with surface water.
  This is simulated by the lower value of n.
- m: It is felt that the higher value for m in case of groundwater is caused by the larger diameter grains which are used. Apparently Lerks's formule does not model properly the influence of the grain size.

7. DISCUSSION

In this paper we demonstrated the use of the Lerk-Maroudas model to simulate filter performance. Computer programmes for the simulation as well as for the calibration of the model can be executed on a micro computer, such as the IBM-PC. With the micro, the design engineer has a powerfull tool in evaluating the effect of design alternatives. Furthermore, the micro can be used to calibrate the model by selecting values for the variables respesenting floc size and composition. Moreover it is easy to carryout a sensivity analysis of these parameters which again improves the reliability of the results.
From a survey of field plants it was found that the model output can simulate quality improvement and head loss development of a wide range of filter plants, provided the proper values are selected for the variables representing floc size and composition.
Nevertheless it is recognized that large differences occur between apparantly comparable filters. Therefore it is concluded that the model calculations should not be used to avoid the use of pilot-plant investigations. However, the combination of pilot-plant research and model calculations does have promising prospectives in optimizing design of drinking water filtration plants.
It is recommended to perform model calculations for a large number of field and pilot-

plants. The results could be used as a database and improve insight in the possibilities and limitations of filtration models. One conclusion of the survey presented today would be that the model of Lerk-Maroudas can simulate field performance fairly well; another tentative conclusion is that the influence of grain size on labda0 in the model is too pronounced.

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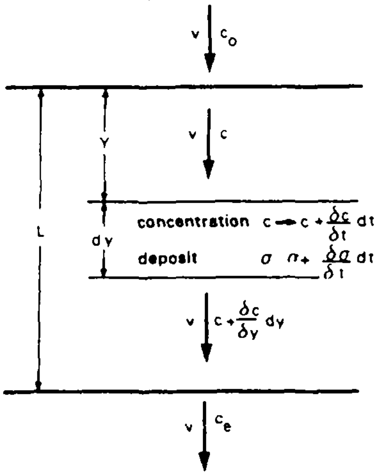
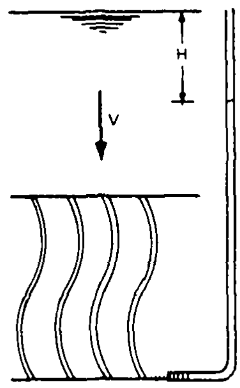
Water quality/solids removal



Head loss development



Basic differential equations

1 removal $\frac{\delta C}{\delta y} = \lambda C$

2 clogging $\frac{\delta C}{\delta y} = \frac{1}{v} \frac{\delta \sigma}{\delta t}$

With $\lambda = \lambda_o \left(1 - \frac{\sigma_v}{n p_o}\right)$

and $\sigma = \sigma_v \times \rho$

the analytical solution becomes

3 $C = C_o \times \frac{e^{\alpha t}}{e^{\lambda_o Y} + e^{\alpha t} - 1}$

4 $\sigma = n \times p_o \times \frac{e^{\alpha t} - 1}{e^{\lambda_o Y} + e^{\alpha t} - 1}$

where $\alpha = \frac{v \times C_o \times \lambda_o}{n \times p_o \times \rho}$, $\lambda_o = m \times \frac{9 \times 10^{-18}}{\nu . v . d^3} = m \times \lambda_o$ (Lerk)

Capillary filter model

5 clean bed head loss $H_o = \frac{180}{g} \nu \times \frac{(1 - p_o)^2}{p_o^3} \times \frac{v}{d^2}$ (Karmen-Kozeney)

6 foul bed head loss $\frac{H}{H_o} = \left(\frac{p_o}{p_o - \sigma_v}\right)^2$

With the solution of 4 the foul bed head loss becomes

7 $$H = \frac{H_o}{\lambda_o Y} \left\{ \frac{\lambda_o Y}{(1-n)^2} - \frac{n^2 (e^{\lambda_o Y} - 1)(e^{\alpha t} - 1)}{(1-n)(e^{\lambda_o Y} + (1-n)(e^{\alpha t} - 1))((1-n) e^{\alpha t} + n)} - \frac{n(2-n)}{(1-n)^2} \ln \frac{e^{\lambda_o Y} + (1-n)(e^{\alpha t} - 1)}{(1-n) e^{\alpha t} + n} \right\}$$

LEGEND:

C, C_o =	concentration solids in water	(g/m^3)	v =	filtration rate	(m/s)
σ =	gravimetric concentration of deposits	(kg/m^3)	t =	filter run length	(s)
σ_v =	volumetric concentration of deposits	(m^3/m^3)	Y =	depth below top of filterbed	(m)
ρ =	mass density of solids	(kg/m^3)	l =	depth of filterbed	(m)
λ, λ_o =	filtration coefficient	(m^{-1})	g =	gravity constant	(m/s^2)
p_o =	porosity of clean filterbed	(m^3/m^3)	H, H_o =	head loss over filter	$(m\ H_2O)$
n =	maximum fraction of pore filling	(fr.)	d =	hydraulic diameter of filter grains	(m)
ν =	kinematic viscosity	(m^2/s)	m =	multiplying factor labda	(dim less)