SURFACE WATER TREATMENT AND ITS OPTIMIZATION BY A SPECIAL FILTERING TECHNIQUE

Suspended Solids in Surface Waters and their Elimination by Coarse-Grained Filters.

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concept 1973

A. INTRODUCTION AND AIM

Within the Ruhr-District (Germany) artifical ground water recharge is the wide spread process of gaining water for public water supply. The works of the city of Dortmund use the raw water of the Ruhr river. Formerly it got infiltrated by slow sand filtration into the subsoil and it was regained after subsoil migration by perforated concrete pipe at a depth of 7 meters. More than a decade ago the direct loading of raw water had been felt to be to expensive, because an increasing water demand and increasing wages gave emphazise to the cost of regular filter cleaning, a necessity every six weeks as an average, in case of bad raw water quality necessary even after a few days of slow sand filter operation. In reducing costs of operation - and in getting more security of operation - a prefiltration stage had been inserted to reduce the suspended solids load from slow sand filters and thus to lengthen the slow sand filter running period. Picture 1 gives the changed system schematically. This prefiltration is effected by coarse grained filters, each of a length of filtration of about 50 - 70 meters, about 70 meters broad, and the total thickness of the filter bed varies from 1 meter to 1,5 meters. On top of the filter bed there is a 0,4 meter thick layer of 5 - 12 millimeter gravel, thereunder 30 - 70 millimeter diametered gravel is chosen. The raw water percolates via a cascade upon the filter bed, percolates downward and flows to the end of the filter bed, where a perforated concrete pipe serves as drainage, from where the prefiltered water goes over cascades to the slow sand filters.

By means of a research project an investigation of the coarse grained filters had been made possible, aiming at:

1) definition of an applicable method for determination of suspended solids
2) determination of the regime of suspended solids within a surface water
3) quantification of suspended solids removal by means of coarse filter grain
4) change of chemical and bacteriological water quality during filtration over coarse grained filters
5) principles of filter dimensioning
6) principles of operational conditions
7) optimization of economy

Results of thus orientated investigations enable a complete opinion as regards to the overall efficiency of the whole process.

B. SUSPENDED SOLIDS DETERMINATION

The raw water even is of such quality under normal conditions that a sensitive method had to be found to determine suspended solids content. Systemical investigations led to the use of membrane filters, MF 250 Sartorius, loaded by 500 ml sample and gravimetrical determination of the suspended solids residue. For a 1,17 ppm mean of ten results the mean deviation had been computed as 10,4% following to SNEDECOR.

C. REGIME OF SUSPENDED SOLIDS

As for practical scopes the point of draft for raw water is of importance the distribution of suspended solids over a river's cross section should be known. With the idea of KARMAN for transport of mass within a suspension in a turbulent state and with KEULEGAN's ideas concerning velocity distribution a balance of mass transport gives finetily

$$C = C_o\, e^{-\frac{s k}{2 \beta l^2} \sqrt{\frac{\tau}{\rho}} \left(y^2 - y_o^2\right)}$$

as the relation between suspended solids concentration and level.

Herein is

C	suspended solids concentration at elevation y above river bed
C_o	suspended solids concentration at elevation y_o above river bed
s	sedimentation velocity of suspended solids
k	constant
β	constant
l	mixing length according Prandtl
τ	shear tension at river bed
ρ	density of suspension

The actual measurements of suspended solids distribution led to a constant one over the entire cross-section, even at low water velocities of 8 cm/sec. In view of the above developped term for distribution it has to be concluded a very small sedimentation velocity of suspended solids. However, mention has to be done to the fact that during periods of floods suspended solids concentration exceeded 15 ppm even reaching a level of a multiplied value sampling at different points of the cross-section was due to extreme velocities and decreased security impossible.

Regular observation of suspended solids concentration at intervalls of three hours and evaluation of these data by computorized mathematics reveal relations between river flow and suspended solids concentration as an increment of river flow from lower than 15 m^3/sec to 30 m^3/sec within 6 hours will bring aforth an increment of suspended solids concentration within one hour. This increase in concentration will effect a raw water concentration of larger or equal 15 ppm critical with respect to the coarse grained filters. A smooth increment of flow 15 m^3/sec and thereabove up to 40 m^3/sec will draw the consequence of an increase in concentration inert three hours.

The first mentioned regularity holds for summer.

A steady control of the flow gage by supervising personnel will lead to an effective control of the inlet devices. Protecting filters from bad water quality requires storage capacity. Providing storage capacity there arises the question concerning duration of bad raw water quality events. Sample evaluation leads to picture 2. First-filter-stage-practice shows the conveniency avoiding suspended solids concentrations equal or larger 15 ppm. This condition accomplished coarse grained filters protect secondary slow sand filters from increased suspended solids load. Thus necessitating a 200 hr-draft-storage volume.

Regarding an entire year the coarse grained filters would have to be out of service for 1200 hrs as a whole. Picture 3 shows duration curve of suspended solids concentration.

Picture 4 gives suspended solids content versus time both being daily mean value. Sample point is nearly identical with raw water drawing place. The mean of suspended solids results from eight samples taken at intervalls of three hours. In fact actual peak will exceed averaged values by a factor of about 2.

As to volatile part of suspended solids picture 5 gives an idea of variation with absolute content and its dependance on saisonal influence. Months of developping vegetation as may 1968 show a steep increase and august 1968 with heavy sunshine and extreme temperatures a high percentage of volatile part. During the change of the year it is low comparatively, and even june 1968 having been extremely cool does correspondingly, although belonging to summer time.

It has to be said that raw water off take point is placed within a shallow lake of some meters depths and thus bioreaction upon rising temperatures and sunshine is extremely quick. The straight lines shown substitute an orientiated collective of points, one for every day.

D. QUANTIFICATION OF SUSPENDED SOLIDS REMOVAL

D_1 PILOT INVESTIGATIONS

As investigations on suspended solids removal of the large scale first-stage-filters according to picture 1 can produce knowledge of the effect of a two-layer-system only half-scale tests had been run to get differentiated removal behaviour: a filter bed of a length of 4 meters of filtering length, of a width of 0,7 meters and of a height of 0,6 meters had been filled with the following coarse media respectively: 5 - 12 mm, 30 - 70 mm and 80 - 250 mm. Each filter medium was run for a period of two months. Thus variation of hydraulic load, raw water quality and temperature was possible. And adaption of the filter material versus changed conditions could be waited for.

Samples could be taken at small distances at start and increasing distances with increased filtering length. Sampling tubes of 6 mm diameter took water from a lamina near the first third of the filter width.

Results of half-scale investigations give pictures 6a, 6b and 6c for raw waters with suspended solids of 5 ppm respectively 8 ppm. Hydraulic load is given by its specific value in m^3/h and m width of the filter bed and the filtering velocities are drawn with respect to filter way. Filtering velocities have minimum values from 20 m/h to 60 m/h and climbed up to 150 m/h at the end of the filter bed with mostly lowered water table.

As the filter way of 4 meters corresponds to the height of trickling filters it is worth to note that 25 to 30 percent of the suspended solids are retained by the coarsest material, although their inclination for elimination is rather small. In view of the chance to enlarge the filter way up to some decades of meters the amount of removal may be multiplied. Deeper insight to elimination mechanisms is due to consideration of suspended solids removal versus filtering velocity during corresponding intervals, showing a slight increasing elimination rate with increasing filtering velocity. It looks like that this rise is initiated in the range of velocities critical with respect to turbulence. This may be due to multiplied chances of contact between the grain surface and the single suspended particle, as indicated in the above given formula for the elimination of suspended solids.

To confirm this idea laboratory investigations had been run. The material used was from 0,2 - 0,6 mm via 1,0 - 2,0 mm and 2,0 - 3,0 mm up to 4,0 - 6,0 mm. The depth of the sand layer was chosen proportional to the filtering velocity to make sure equal detention periods within the filter layers. This parameter constant suspended solids removal may show open to variation in conditions of flow. Velocity ranges below turbulence removal decreased with increase in speed, corresponding to growing shear between grain surface and fluid. Whereas an increase in removal is achieved at higher velocities. The only possible positive component seems to be given by flow conditions exceeding the detrimental effect of shear.

As these coarse grained filters protect the secondary treatment stage an adaption to shock-like increases of loading is of minor significance for operation of the treatment system. Anyhow checks of suspended solids removal were done showing a negative reaction following to shock immediately and a complete adaption within two and a half hours.

D_2 TECHNICAL SCALE INVESTIGATIONS

Coarse grained filters being in operation since a good deal of years were investigated also. As mentioned above with respect to half scale filters tests were run over a period of about two months, whereas technical scale filters are in operation for five or six years without being cleaned or washed.

This extreme running period is due to voluminous pore opening of the coarse grain, due to the large filter bed volume, due to the phreatic water table's elasticity against increasing flow resistance as a consequence of deposits within the pore space, due to the large surface of the filter which facilitates a smooth flooding of the surface when filter regions near to the entrance region of water are clogged too much and the zone of infiltration is shifted towards the end of the filter. The last mentionned mechanism increases the hydraulic gradient driving the water through the remaining filter way.

This extended period leads consideration to the filter behaviour in the long run, as the positive component of the filter's coming into stride may be overbalanced by a possible effect of aging, the latter getting significance as filter operation endures.

Filters were investigated at an operational Age of one month, then ~~in operation~~ at an age of seven months and at an age of nineteen months.

The hydraulic load was driven up to its maximum hydraulic capacity. In between any raw water quality's behaviour passing the filter was observed.

In facilitating sampling 1 1/2 inch pipes were driven into the filter bed of about 1 m depth. Wholes of 1 cm-diameter at distances of 10 cm achieved connection to the water filled pore space. Sampling was done by a centrifugal pump; it was started by prepumping for 2 minutes at total capacity, there followed a reduction to 25 ml/sec maintained for 2 1/2 minutes before filling the 500 ml-bottle. Further bottles were filled to extend determinations on chemical and bacteriological aspects.

Picture 7 gives the characteristic line for reduction of suspended solids content during filtration by the large scale filters. The line holds for the age of one month. Although a considerable reduction occurrs up to a filter way of 4 meters, as observed with half scale tests, further diminution of suspended solids takes place with increasing filter way. The lines are parametered according to specific hydraulic load expressed by m^3 (raw water inflow) per hour and m (running meter) breadth of filter. For sake of perfection water temperatures are added. The dotted parts symbolize the flooded filter bed surface regions increasing when the ratio of water quantity and corresponding resistance develops to be unfavourable. This development depends from multiplied hydraulic load and from clogged surface zones as a factor of aging.

With usual suspended solids concentration load to slow sand filters can be reduced by about sixty percent at traditional hydraulic load of 10 m^3/hr rm, resulting in filter velocities of 20 m/h (see picture 7).

There it has to be said that the suspended solids composition is not constant. Their volatile part is due to variations, seasonal ones and climatic ones. (~~Those will be discussed in detail later on.~~) Due to seasonal variations volatile components may vary from 10 to 50 percent, at suspended solids content itself of 5 ppm and river flow conditions comparable. These differences will result in varying removal behaviour as seen from picture 8. The increased percentage of volatile components parallels a remarkable diminution of removal. Both results are derived from two separate filters with an age of one month following to regeneration. Indeed hydraulic load differed by fifteen percent, but as is shown by picture 7 from this difference there does not entail such considerable change.

A difference in temperature of six degrees Celsius seems to increase the chance for removal of the more volatile samples.

It does not seem necessary to cite pictures with the suspended solids removal line holding for a filter of an age of nineteen months. Due to a progress of clogging the flooded surface area had increased and the way of filtration will be shorter, the typical removal behaviour does not change. It may be added that the covering layer of 5 to 12 mm gravel will promote surface clogging to a farer extent than a more coarse material would do. Later on this will be discussed in view of operational aspects.

Reviewing filtering mechanisms might not be the place here, anyhow attention should be drawn to one component being sedimentation, because a simple computation may elucidate its significance, in this special case. Remembering picture 1 facilitates the idea that this filter is flown through horizontally - grossly spoken. Let us say that the medium grain dimension of the 30 to 70 mm grain is 50 mm. Then a filter bed of a height of 1 m consists of 20 sedimentation basins of rather small depth, so the hydraulic load makes 5 percent compared with a sedimentation tank with 50 x 70 m^2 surface. Following to STOKES and CAMP the removal ratio concerning a sphere of a 10^{-2} mm diameter having a density of 1,02 or 2,65 would be 20 or 100 percent respectively. These values hold for a floc of sludge and sand respectively. In view of the origin of suspended solids and in view of their volatile component one may assume the density of suspended solids to be larger than 1,02.

The result of this reflection should not give rise to the misunderstanding that the author likes to abolish the existence of other filter mechanisms, like physical, chemical or biological ones. Anyhow, this effect of sedimentation explains the dependence of reduced removal at higher volatile component.

E. CHANGE OF CHEMICAL AND BACTERIOLOGICAL WATER QUALITY

Consideration of chemical and bacteriological components shows the existence of a complexity of components. In keeping small this paper it may be cited that during filtration NH_4^+ is oxidized completely almost, content of nitrate increased, oxygen content and BOD do the reverse as do COD, coli and germs.

F. PRINCIPLES OF DIMENSIONING AND OPERATING FILTERS

The following part gives a summary in achieving a consequent construction and operation of these filters.

1) As regards to choice of grain investigations showed a remarkable removal of suspended solids up to a range of grain diameter from 80 to 250 mm. This effect is achieved with filtering velocities of 60 m/h. There is no reason to assume a limit given by these datas.

   From this follows that the diameter of grain should be chosen such as to be diminished according to an increase of filter way. Thus deposits could be kept constant over the total volume of the filter bed. This means to install zones of constant grain diameter.

2) The bottom of the filter has to have an inclination into direction of flow to make sure that the fluid will have sufficient speed and deposits will build up from the bottom of the filter to the top in aiming at an equal vertical distribution of deposits.

3) To achieve a constant depth of fluid throughout the longitudinal extension of the filter the inclination of the filter bottom has to be adapted to the resistance of the filtering material within the several zones. Thus the gradient will increase with direction of flow.

4) In view of a possible break-down of oxygen content within the filter there could be planned an intermediate aeration of fluid between two zones of different grains. This measure might be necessary when raw water quality will deteriorate.

5) Up till now regeneration of filter bed material - as told before usual in intervals of four to six years - is done by carrying the filter bed material to a device washing grain by means of shaked sieves sprayed at by hard water jets. The grain is fractionated and filled into the filter volume using conveyor-belts and mechanized ploughs. About six people are sufficient to transact this cleaning prodecure within a period of 6 weeks.

The same work could be done within 8 days using a washing device which is loaded when moving upon the filter ground and which delivers the washed grain immediately.

6) When parts of the filter surface are getting under water insolation promotes algal growth. As to filters in operation it has been mentioned already that the covering layer of finer gravel (5 - 12 mm) facilitates surface clogging and this way development of algae. During the warm period hydrodictyon starts up explosionally.

For the time being this is fighted by intermittent operation and harrowing the dewatered filter surface. As hydrodictyon accumulates at the zone of infiltrating water (where water vanishes) tests had been run laying fine plastic nets upon the surface before the zone of algal accumulation covers this part. Following to it and dewatering the surface the nets containing the masses of algae will be lifted and removed showing that there does not remain a conglomerate of algae and grain. The surface was still clean.

7) As observed that algal growth does not occur within those parts of surface flooded and having higher velocities it should be a criterion of filters to be con-

structed that the surface of the filter bed's gradient is with flow direction. Detention time in flooded parts would be reduced and the effect of insolation, too.

G. COST OF TREATMENT

Investigations and their results as well as elements of construction and operation discussed the question of cost of treatment by these coarse grained filters and economy's point of their application within a system have to be answered. As this problem may be discussed for different conditions in other countries it will be described in detail finitely the results shall be shown.

The structure of cost is given by formulas stating the components. These formulas are derived to describe

1) cost of construction
2) cost of maintainance
3) cost of energy or head loss
4) cost of regeneration of filter (including washing sieves, crader, conveyor belt, energy, labor)
5) cost of cleaning wastes caused by procedure of regeneration.

In simplifying the analysis of cost the formulas hold for a section of 1 m breadth extending over the entire length of the filter construction, including inlet devices as well as contrivances for outlet.

1) Cost of Construction

are built up from two components, the one being independent from the length of the filter because being due to inlet and outlet devices and for a channel serving distribution and collection and due to the construction of a cascade. This overall amount is related to a section of 1 m' breadth, symbolized by a_o (expense / m'). The other component stands for realization of the filter bed, volume of grain and impermeable bottom, related to a section of 1 m' breadth as above and to a length of 1 m, symbolized by α (expense / m^2). Depreciation, interest and taxes is paid regard to by the factor p_B . Expenses per year resulting from cost of construction can be written as

$$K_B = (a_o + \alpha x)\, p_B \qquad \left[expense / m'a \right]$$

x being the length of the grain filled volume in meters.

2) Cost of Maintainance per year (a)
expressed by a formula and written as

$$K_U = (k_o + \varkappa x) \qquad \left[expense / m'a \right]$$

built up with k_o (expense / m'a) for those installations being independent of length of filter and $\varkappa$ (expense / m^2a) for maintainance of filter surface, mainly cost of labour.

3) Cost of Energy (head loss)

Head loss is assumed to be proportional to length of filter. The quantity of filtered water depends upon actual period of feeding raw water. This period is a fraction of the entire period of operation. The latter consists of period of feeding, lack of feeding due to intermittent operation and periods filters cannot be fed during regeneration.

Let be τ_ℓ (a/m) the demand of time as regards to progressive exhaustion of the filter's removal capacity in the case of feeding the filter with a certain quantity of water continually and τ_w (a/m) the specific demand of time when the filter is washed and let be τ_s (a/m) the extension of feeding period by temporary stop of feeding raw water, then one gets an expression showing the actual period of feeding as a function of length of filter way x and as dependent of operational parameters written as

$$\frac{\tau_\ell \, x}{(\tau_\ell + \tau_s + \tau_w)\,x + t'_{wo}}$$

here t'_{wo} (a) is a short period before and after the filter washing, when the filter has to be out of service already.

With cost for energy k_E (expense / Mpm), specific weight of water γ_w (Mp / m^3), specific hydraulic load q_ℓ (m^3 / m'hr), efficiency of lifting water η_{EW}(1), gradient of filter bottom i (1) the total cost for loss of head can be written as

$$K_E = \frac{8760 \; k_E \; \gamma_w \; q_\ell \; i \; \tau_\ell \, x^2}{\eta_{EW}\left[(\tau_\ell + \tau_s + \tau_w)\,x + t'_{wo}\right]} \qquad \left[expense/m'a\right]$$

4) Cost for Regeneration of Filter

sum up from the following components as

movable sieve device with an investion a_s (expense), regarding depreciation, interest, taxes and maintainance by p_s (1), number of filters within the entire treatment system n (1), and breadth of the single filter y (m). This yearly cost can be written as

$$K_{WS} = a_s \, p_s \, \frac{1}{n \gamma} \qquad \left[expense / m'a \right]$$

The yearly cost of the crader can be written as

$$K_{WR} = a_R \, p_R \, \frac{\tau_w \, x}{(\tau_\ell + \tau_s + \tau_w) x + t'_{wo}} \, \frac{1}{\gamma} \left[expense / m'a \right]$$

where a_R is investion, p_R corresponds to depreciation, interest, taxes and maintainance and the coefficient-spiced fraction-term is for frequency and extension of necessary regeneration of filter.

The yearly cost of conveyor-belts is given by

$$K_F = a_F \, p_F \, \xi \, x \, \frac{\tau_w \, x + t_{wo}}{(\tau_\ell + \tau_s + \tau_w) x + t'_{wo}} \, \frac{1}{\gamma} \left[expense / m'a \right]$$

where symbols used are known partly already. ξ is a coefficient relating the total length of conveyor-belts to filter way extension; t_{Wo} is the time required for installing and demounting the movable conveyor-belts.

Costs for energy of conveyor-belt operation is given by

$$K_{WFE} = \frac{k_E \, \gamma_R \, x \, h \, Z_F}{\eta_{EF}} \, \frac{1}{(\tau_\ell + \tau_s + \tau_w) x + t'_{wo}} \qquad \left[expense / m'a \right]$$

with k_E (Mp / m^3) as volume weight of grain, h (m) depth of grain in filter, Z_F (m) medium height of transport and η_{EF} (1) efficiency of conveyor-belt transport.

Cost for labour used during regeneration is given by

$$K_{WP} = k_p \, \frac{\tau_w \, x + t_{wo}}{(\tau_\ell + \tau_s + \tau_w) x + t'_{wo}} \, \frac{1}{\gamma} \qquad \left[expense / m'a \right]$$

with k_p (expense / a) for a complete crew per year. The coefficient-spiced term holds for frequency and extension of regeneration enterprise.

As waste handling plant there is thought of a settling tank with specific digging cost of a_W (expense / m^3 tank), with a quantity of waste q_w (m^3 / hr) and a time of detention t (hr) and p_w for depreciation, taxes and maintainance, this will cause costs of

$$K_A = a_w \; q_w \; t \; p_w \; \frac{1}{u\,y} \qquad [expense/m'a]$$

As the cost of water is given by the expenses facilitating treatment divided by quantity of water treated there will be given the amount of water yearly

$$Q = 8760 \; q \frac{\tau_l x}{(\tau_l + \tau_s + \tau_w) x + t'_{wo}} \qquad [m^3/m'a]$$

These formulas give the basis for computation of treatment cost. Picture 9 shows cost per m^3 water pretreated related to extension of filter way. The curve has a minimum, its existence being due to fast growing expenses caused by frequently required regeneration when extension of filter way is short. Furthermore one can see the contribution of several components. Picture 9 gives the structure of cost with respect to average hydraulic loading and to average suspended solids content, observed during actual feeding periods. Here it may be mentionned that with worsening of water quality expenses grow and the most economic extension of filter way grows, too.

As these prefilters are extending slow sand filter's running period the more the longer the filter way is, the expenses made up by slow sand filters will be changed. Picture 10 shows total treatment cost for prefiltration and slow sand filtration and the structure of cost with respect to the latter. As load conditions remain unchanged superimposed cost for prefiltration is specified in picture 9.

It is shown clearly that prefiltration brings about a remarkable saving in comparison to slow sand filters loaded with raw water directly. Cost for this case are to be taken from diagram at zero point of horizontal axis.

The actual most economic extension of filter way is about twice the above cited one holding for isolated consideration. Total cost increased for about ten percent with respect to respective most economical extension of filter way, when suspended solids content went up from 8,3 ppm to 11,3 ppm. The most economical extension increased as well as absolute amount in saving.

H. THANKS

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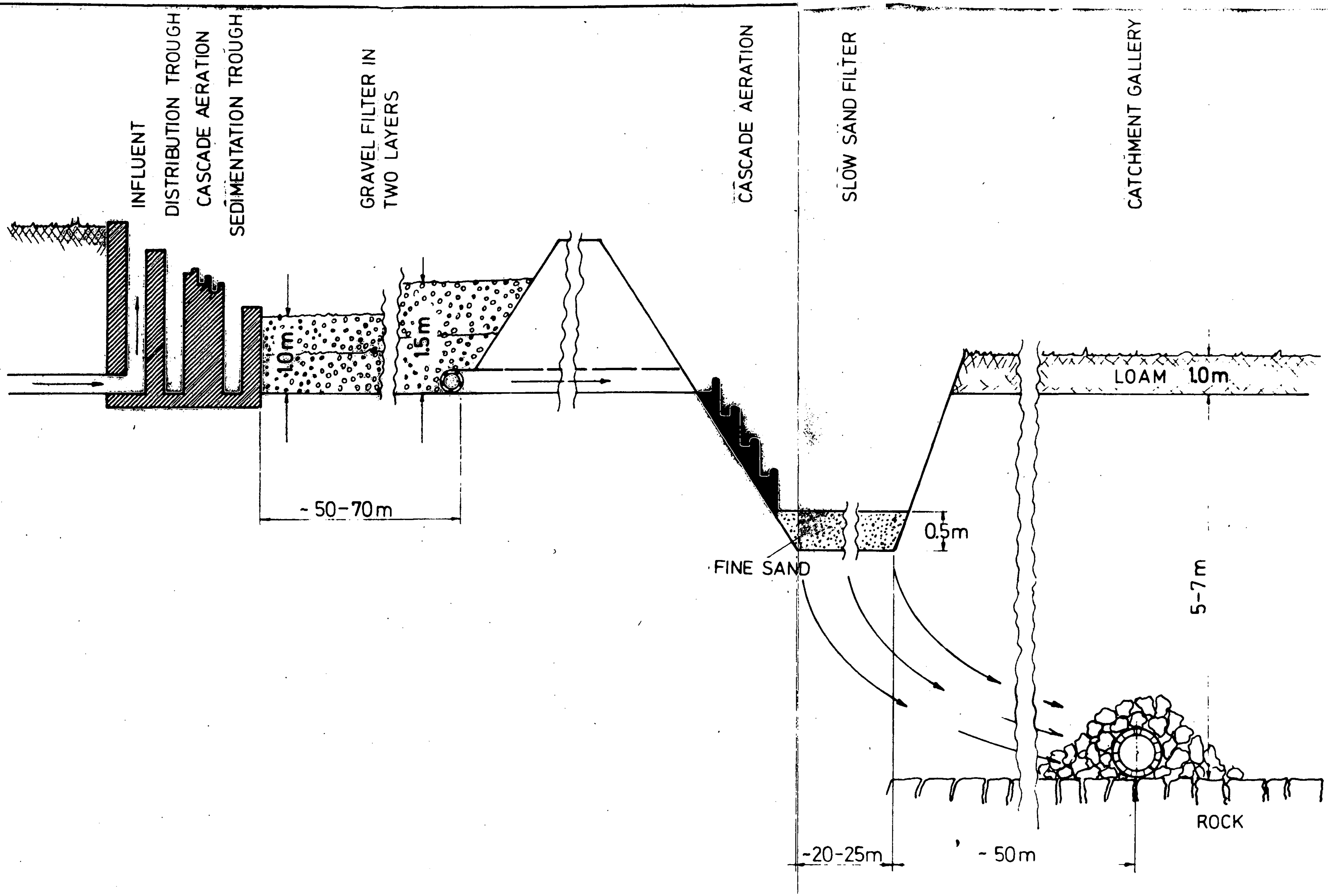
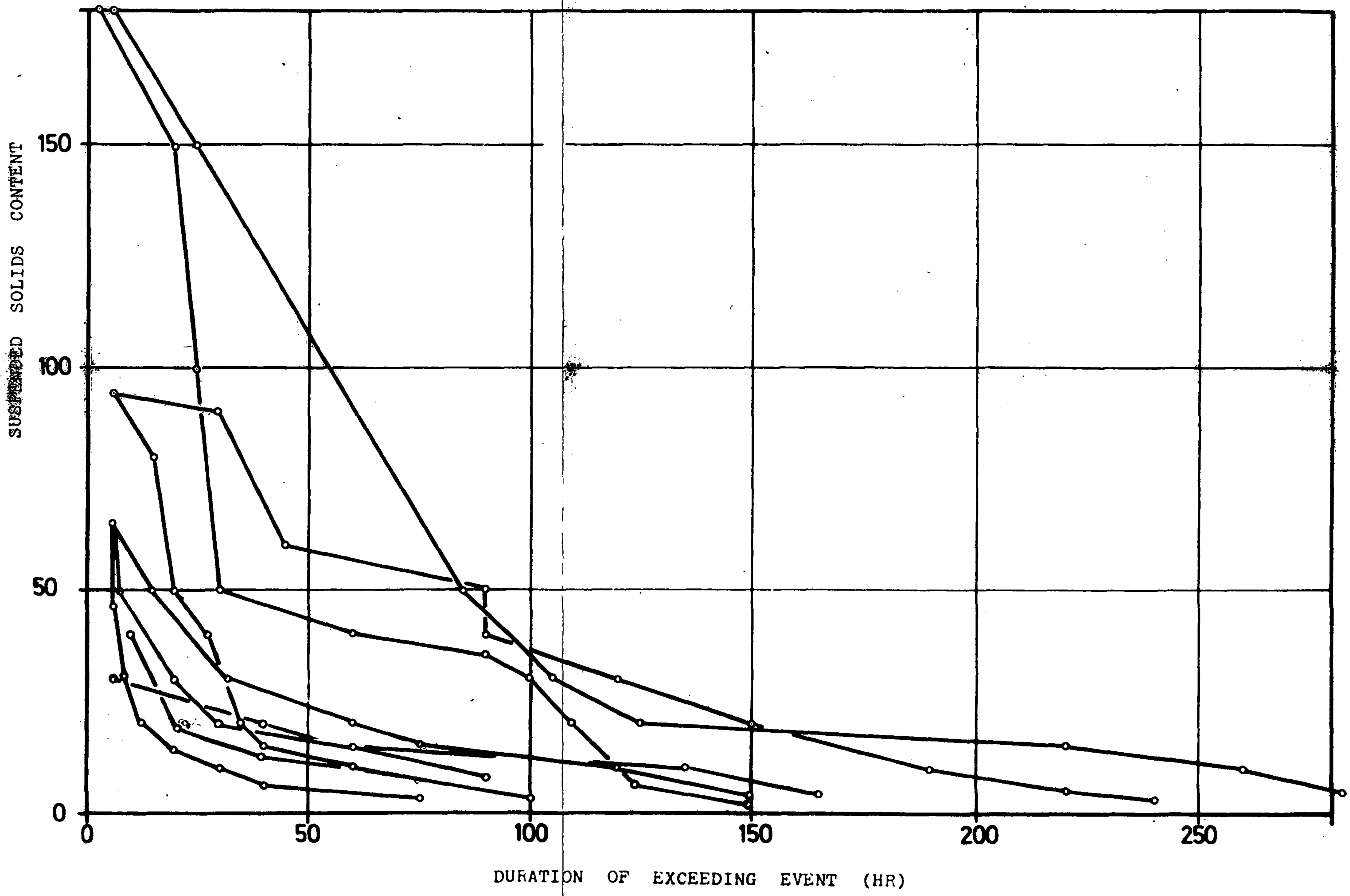


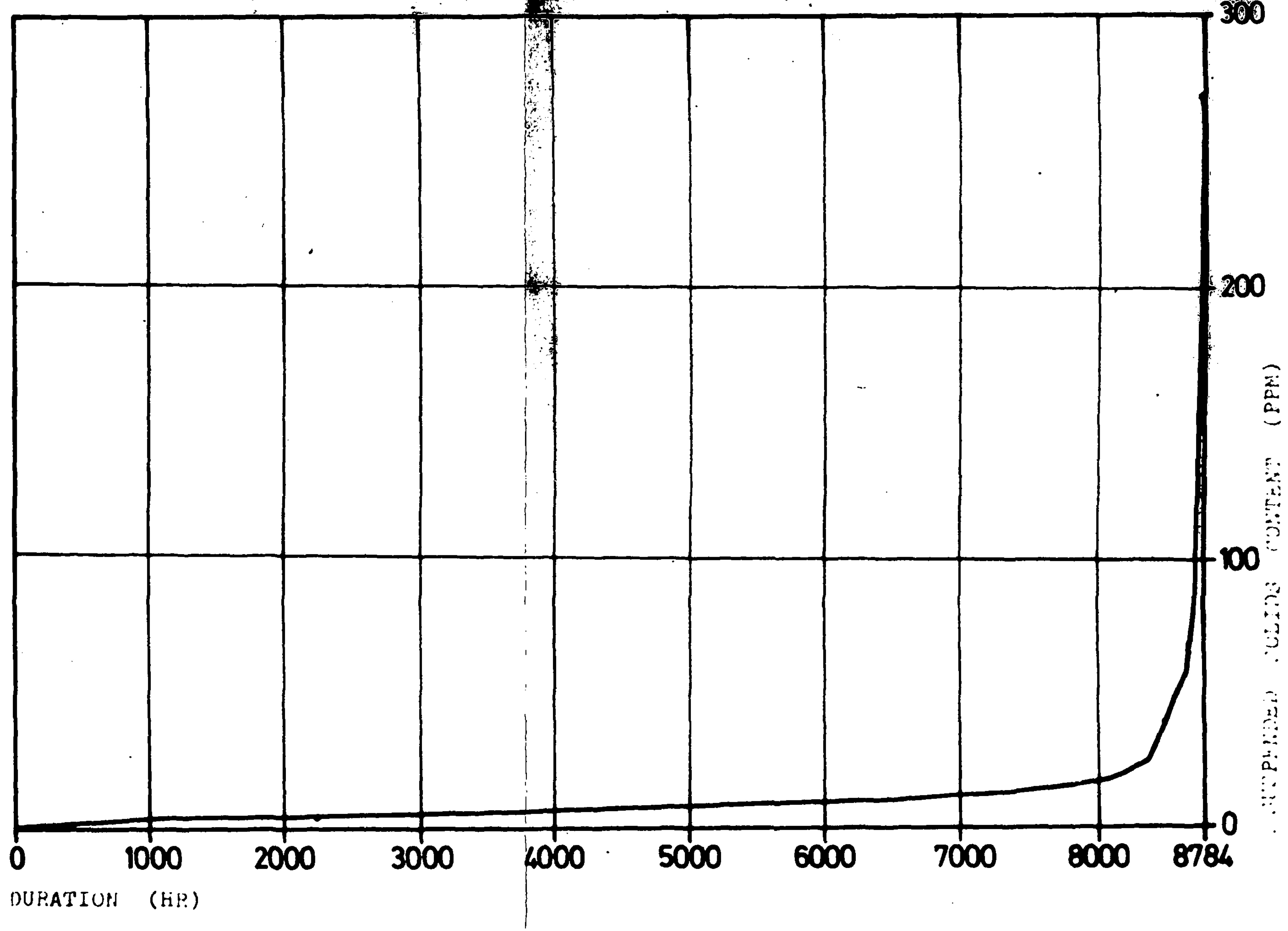
SCHEME OF WATER TREATMENT

1



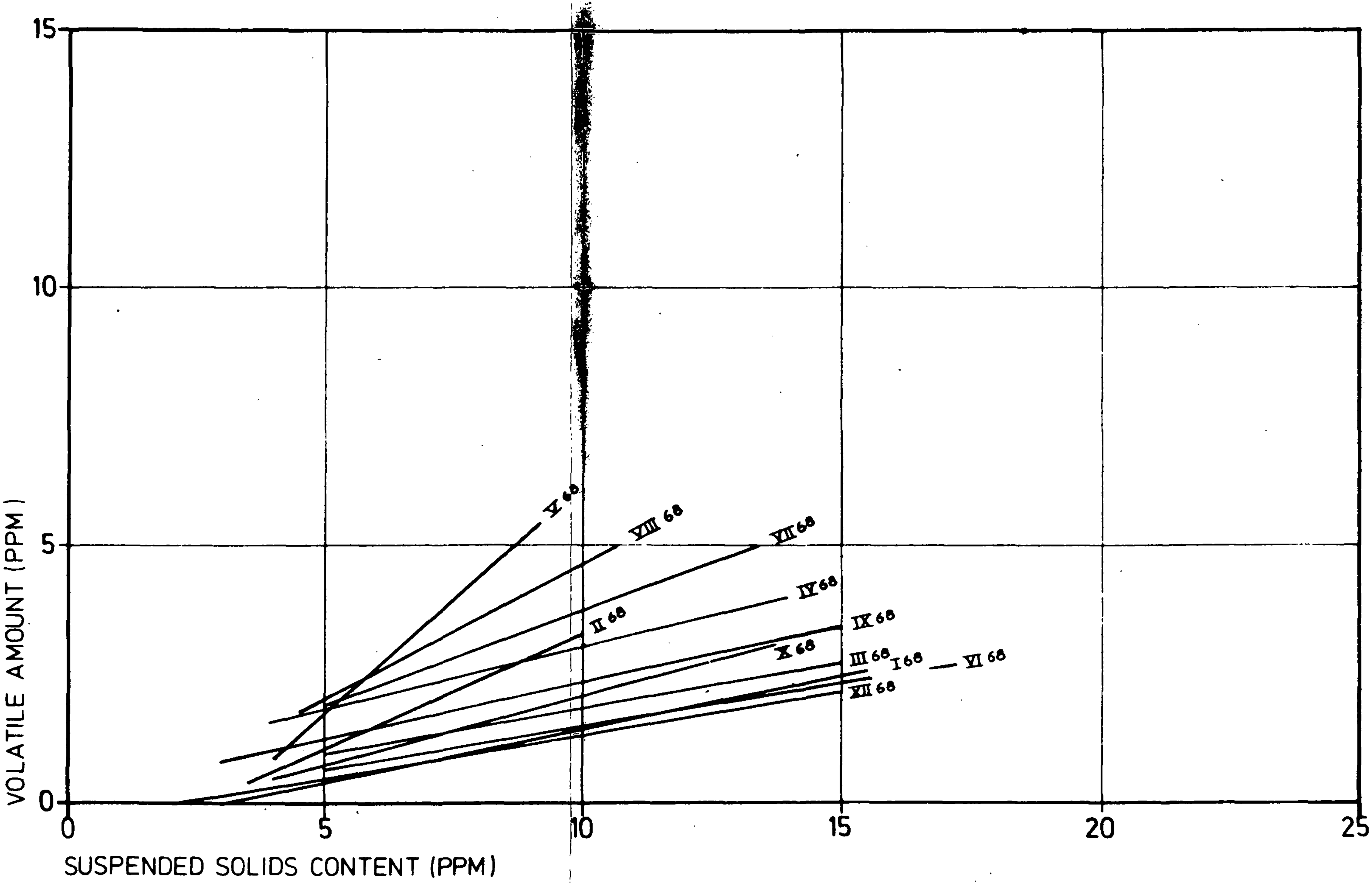
SUSPENDED SOLIDS CONTENT
DURATION LINE
DEC. 1967 - DEC. 1968

2



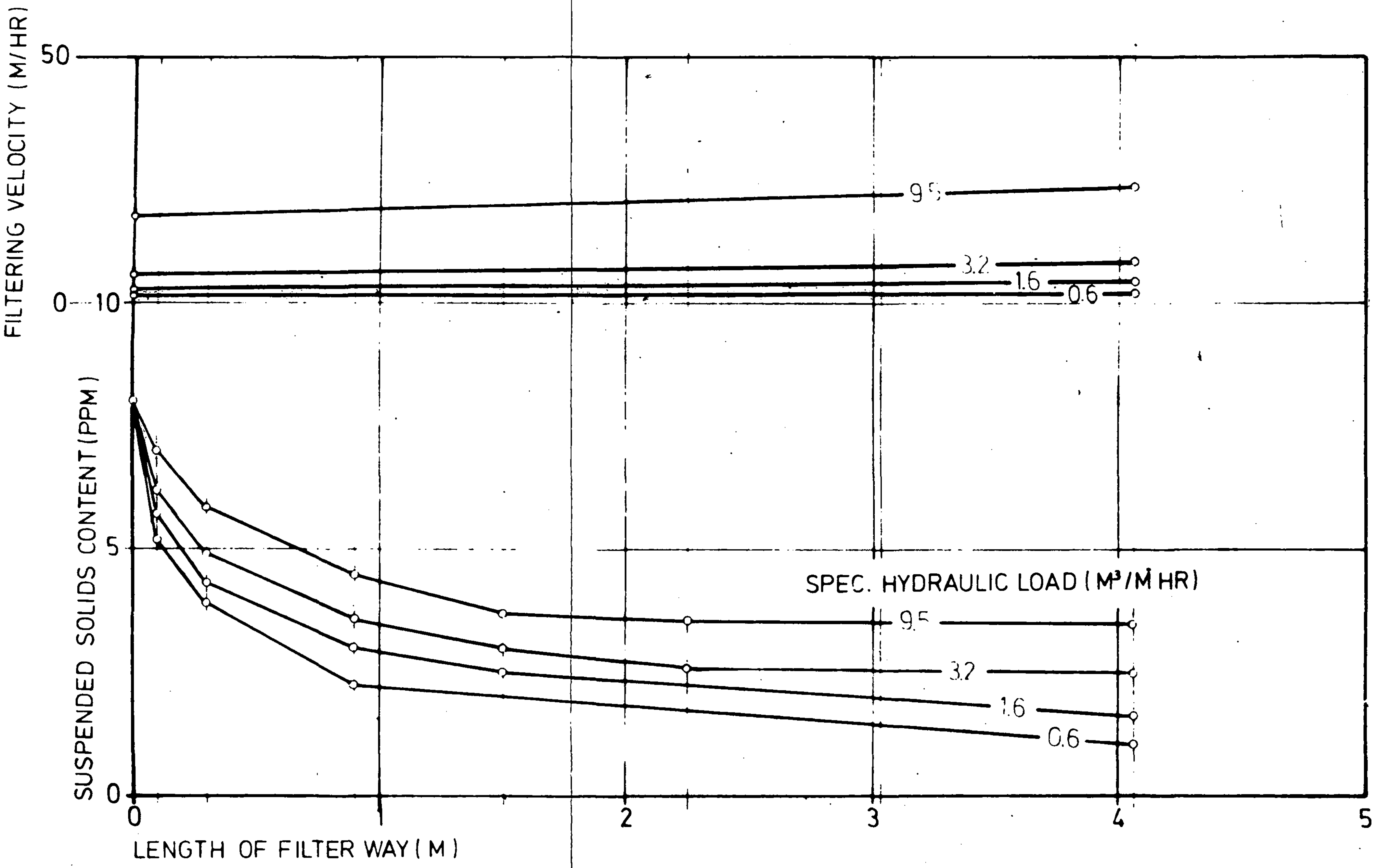
SUSPENDED SOLIDS CONTENT
DURATION LINE 1968

3



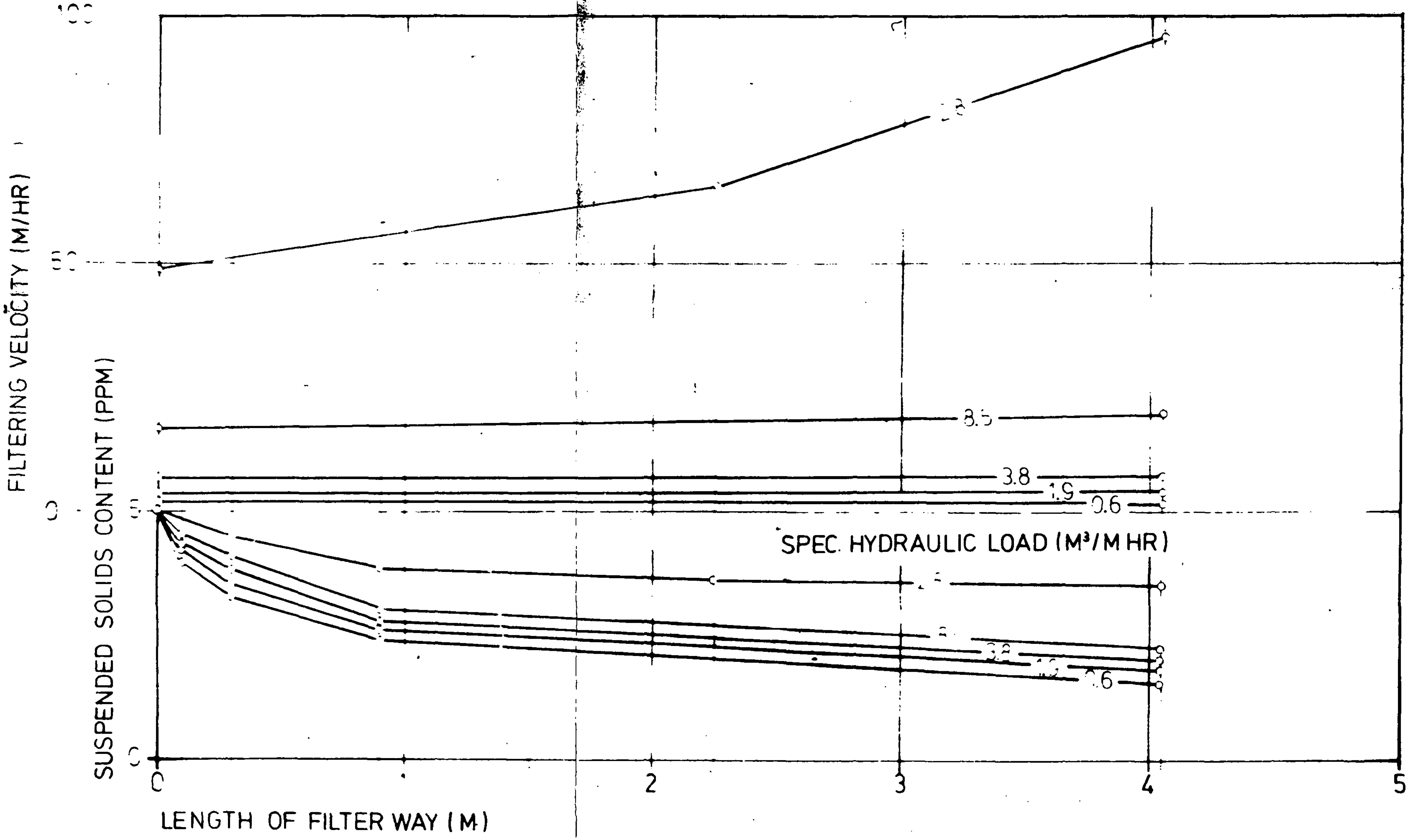
DIFFERENTIATION OF SUSPENDED SOLIDS

5



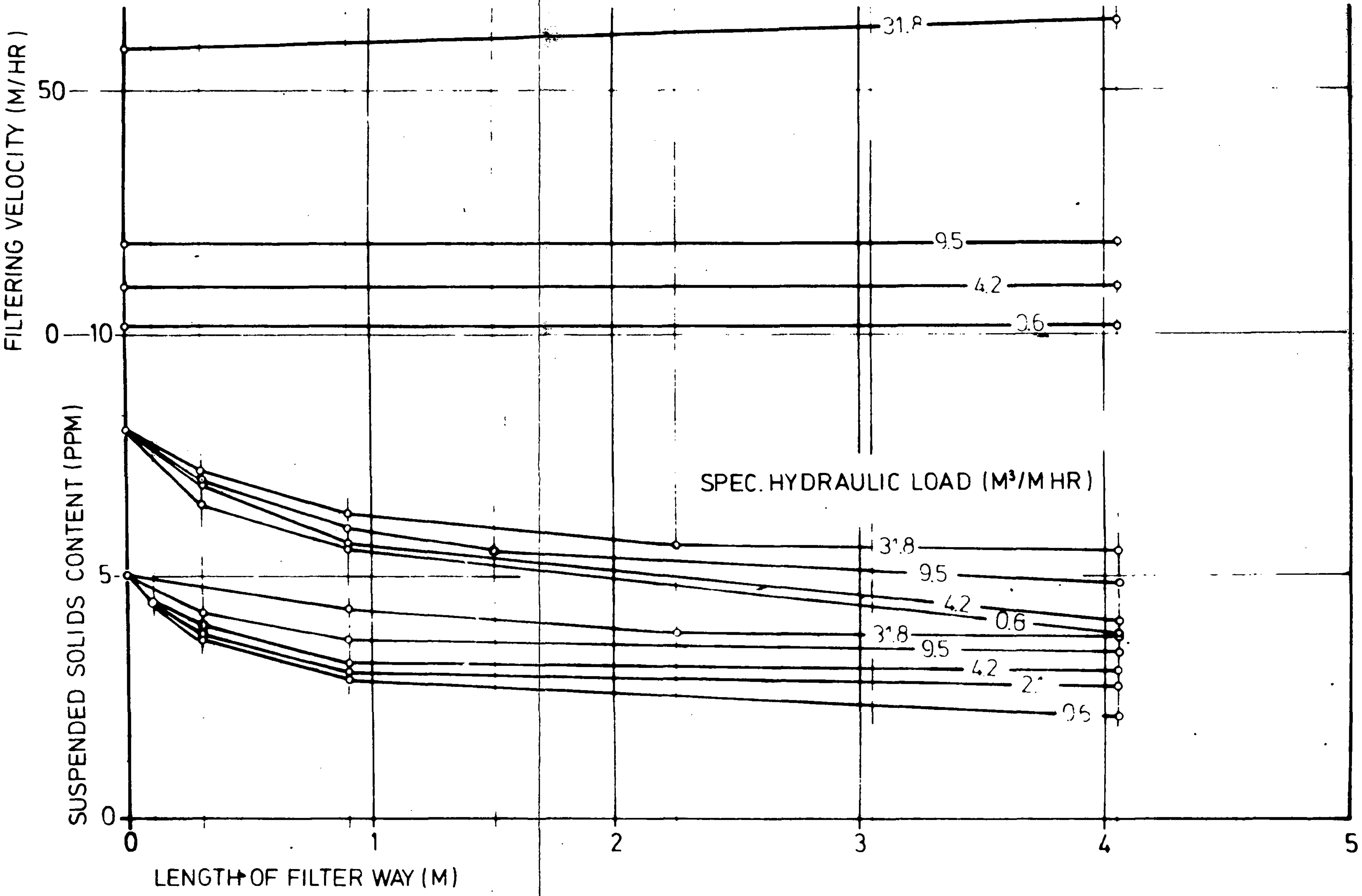
SUSPENDED SOLIDS REMOVAL IN GRAVEL OF 5-12 MM DIAMETER

6a



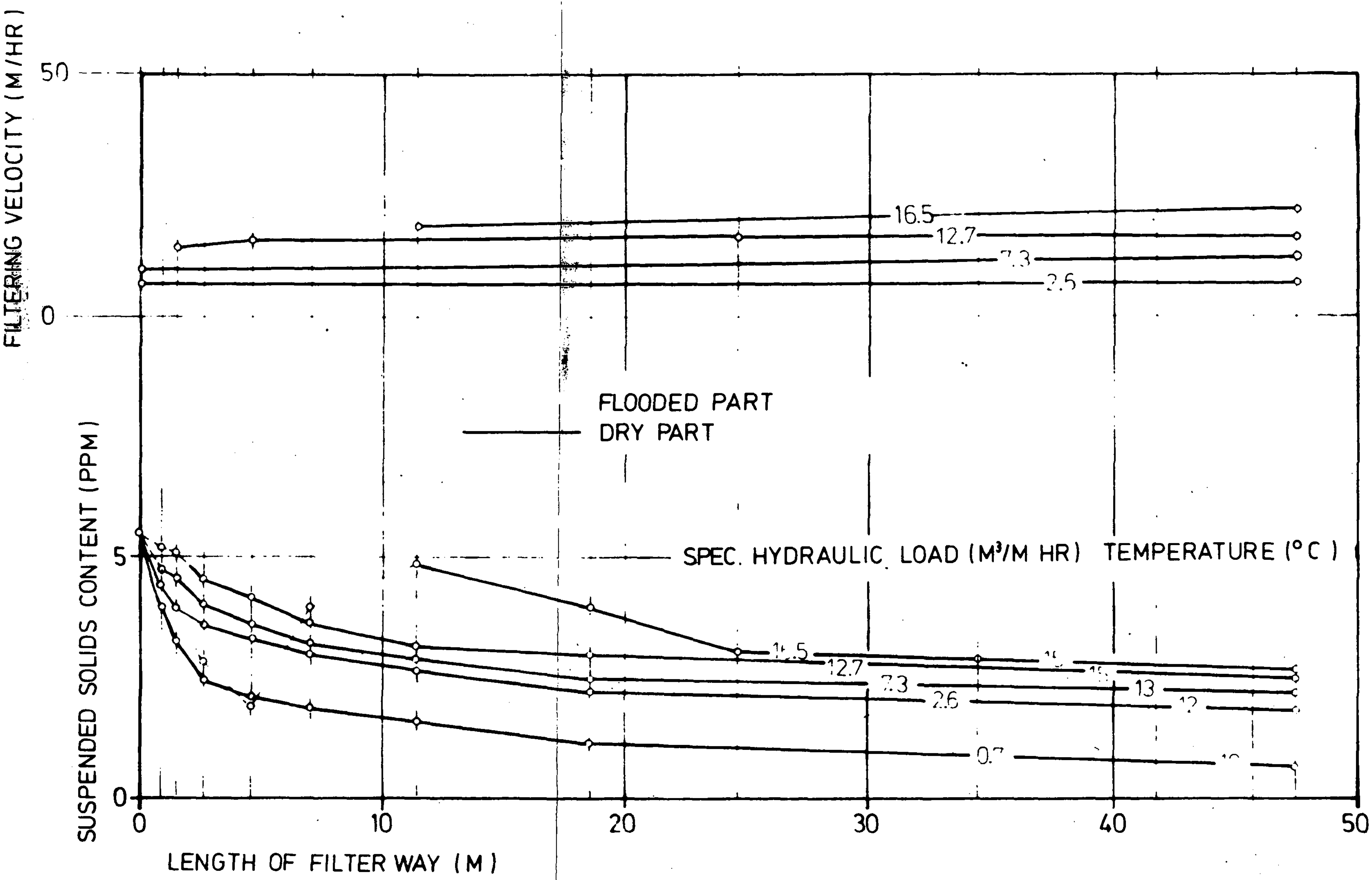
SUSPENDED SOLIDS REMOVAL IN GRAVEL OF 30 - 70 MM DIAMETER

6 b



SUSPENDED SOLIDS REMOVAL IN GRAVEL OF 80 - 250 MM DIAMETER

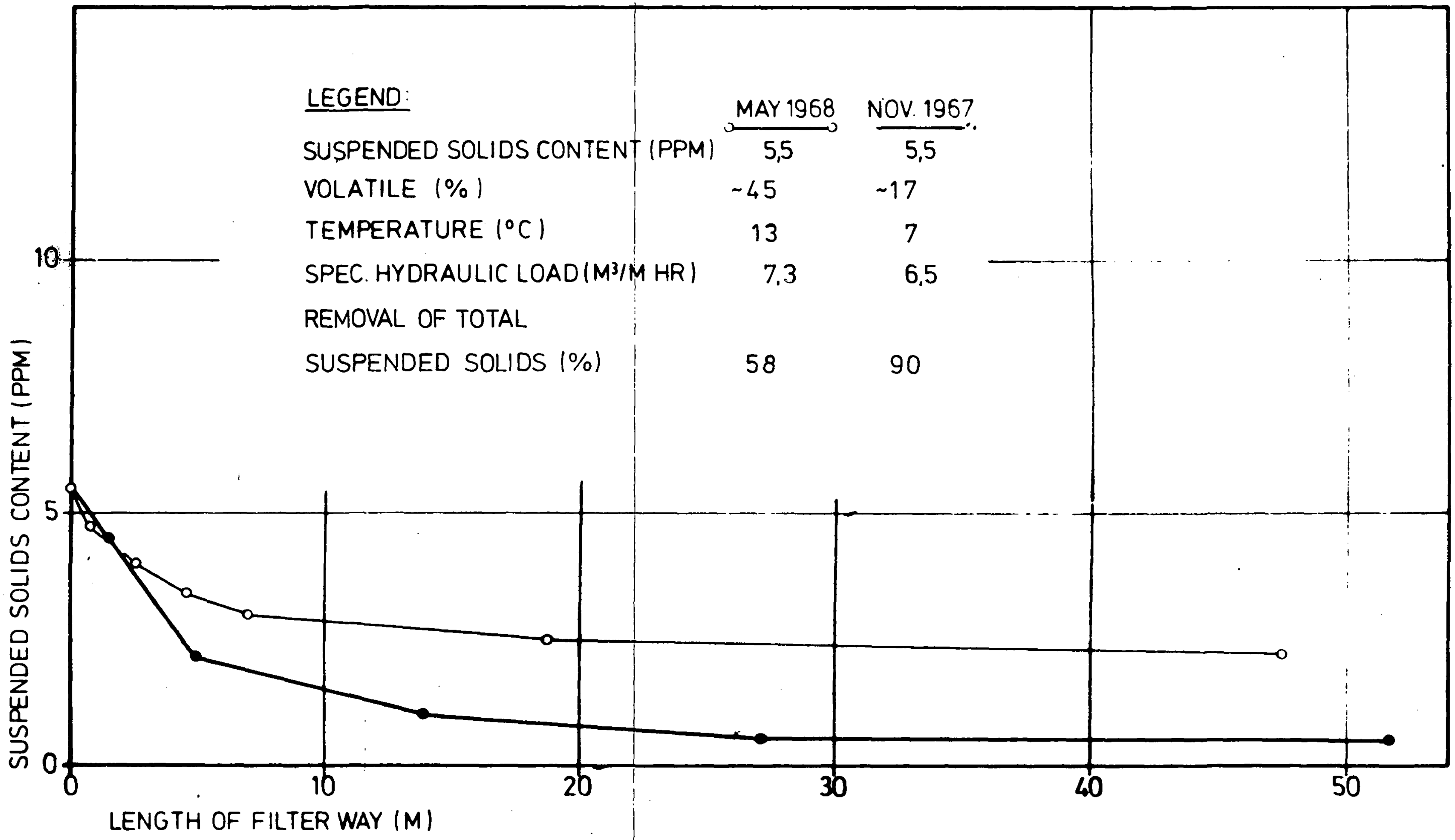
6/c



SUSPENDED SOLIDS REMOVAL IN TECHNICAL SCALE FILTER

[1 MONTH FOLLOWING TO REGENERATION]

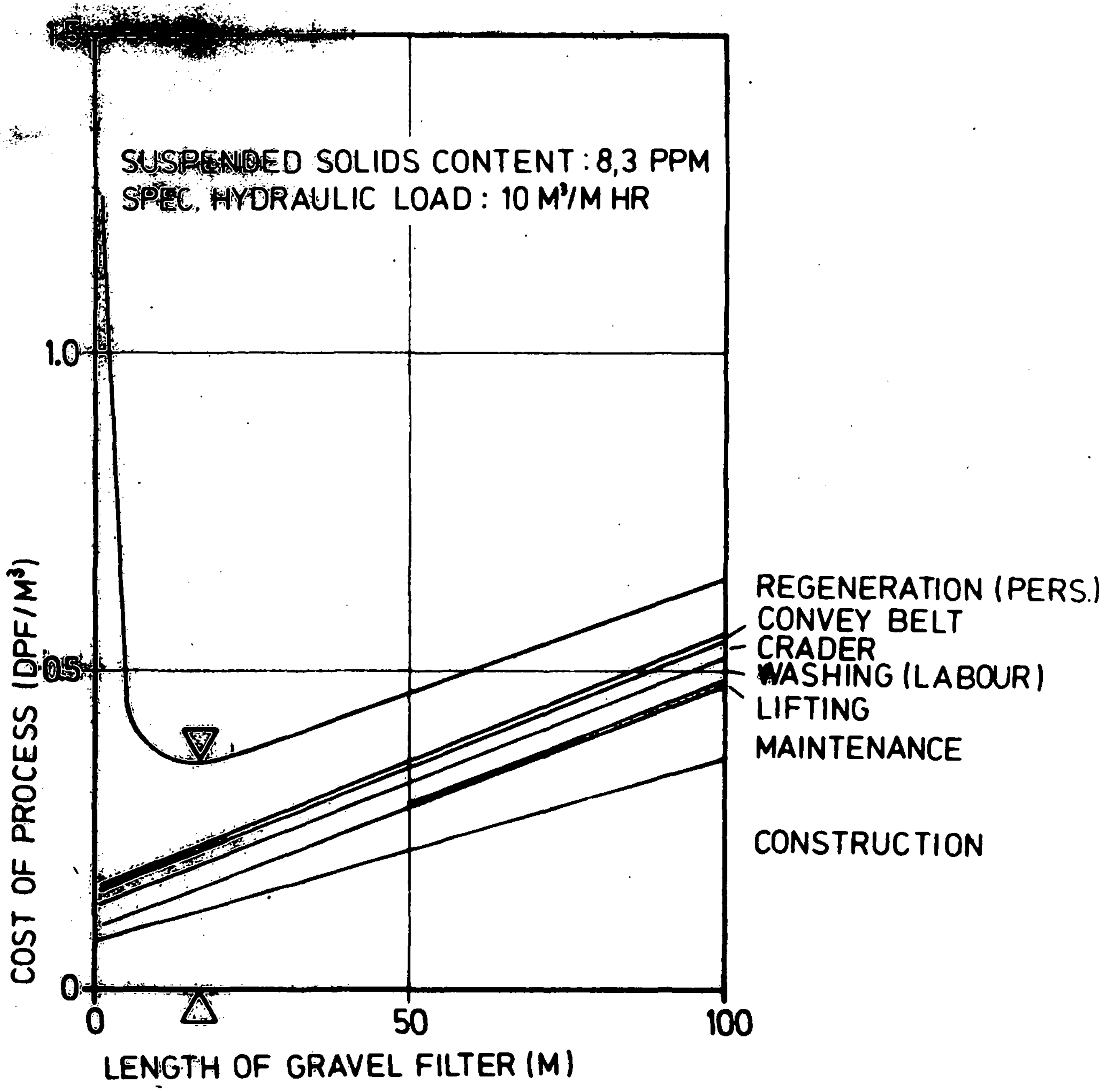
7



SUSPENDED SOLIDS REMOVAL AND VOLATILE CONTENT

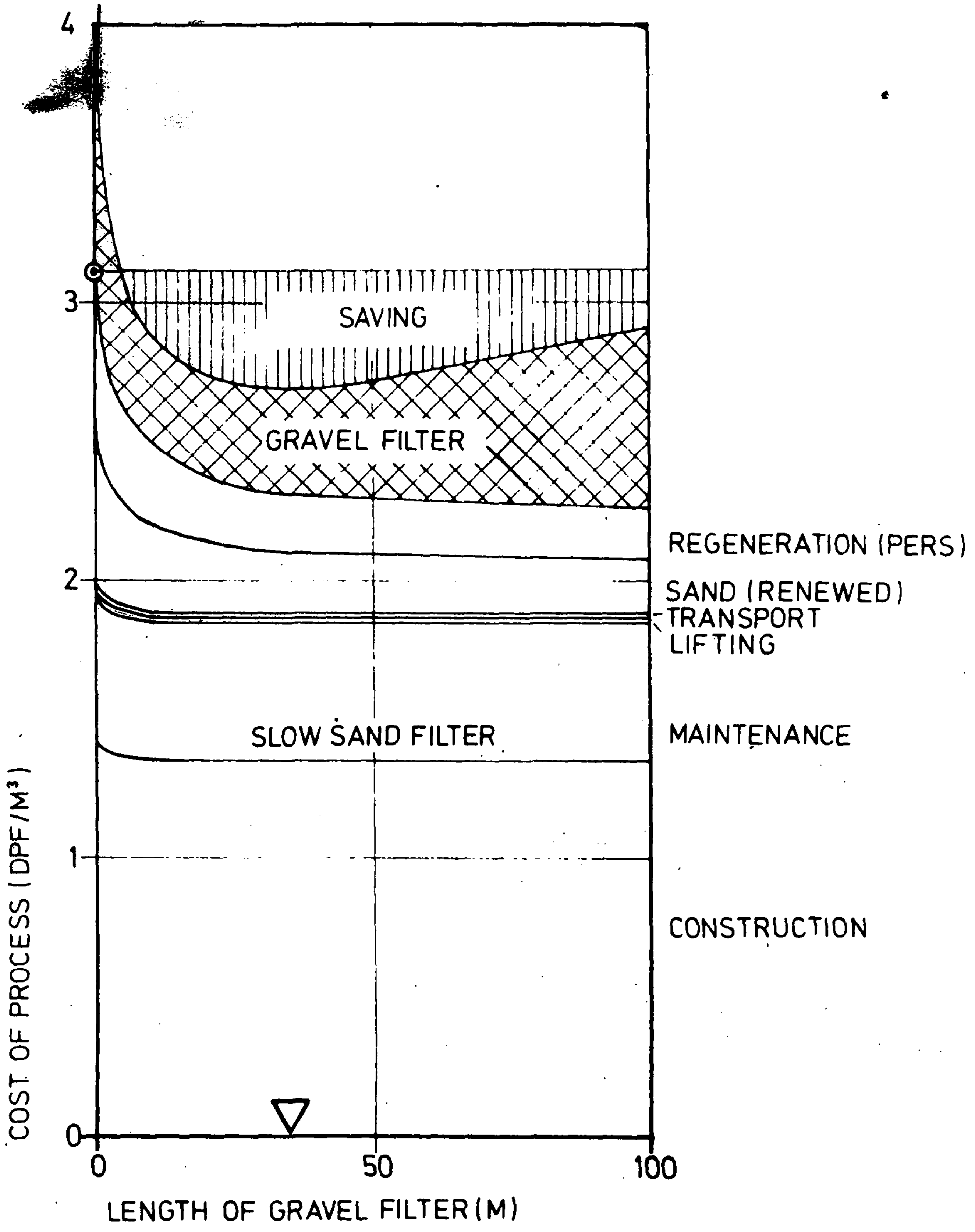
AGE OF OPERATION : 1 MONTH

8



COST OF PROCESS FOR GRAVEL FILTRATION

9



SUSPENDED SOLIDS CONTENT : 8.3 PPM

COST OF PROCESS FOR SLOW SAND AND GRAVEL FILTRATION

10