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An economic approach to establish design capacities for storm drains in the Indus Plain, West Pakistan [1]

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Summary

After a general description of the area and an analysis of the basic hydrological data a method is given to establish the design capacity of storm drainage systems in the Indus Plain on the basis of economic considerations.
Frequencies and duration of inundation and the damage to crops are estimated with surface drainage systems of various capacities. On this basis the benefits of a higher capacity system compared with one of lower capacity can be expressed as the differences in damage to crops.
Estimates are then made of the capital cost and the maintenance and operation costs of surface drainage systems of varying capacity.
After phasing costs and benefits, the present value of both was calculated. The economically justified design capacity can be derived from a graph, showing the marginal benefits for surface drainage systems of varying capacity.

1 Introduction

The Indus Plain, being one of the most extensive alluvial plains in the world, slopes gently down from the Potwar Plateau and the Himalayan Foothills in the north to the Arabian Sea, some 700 miles to the south. The average slope is about one foot per mile. The general topography is flat with some mezorelief caused by free river action which has formed levees and basins, threaded with meanders.
Rainfall is lowest in the central part with even less than five inches per year. To the south, the mean annual rainfall increases to 10 inches near the Arabian Sea. Also to the north the rainfall increases gradually up to an annual mean of more than 30 inches near the Himalayan Foothills. Although rainfall may occur throughout the whole year, about two thirds of it is concentrated in the months of July, August and September. This seasonality and the very high temperatures prevailing from April to October (up to 115° F in June) makes agriculture in the Indus Plain almost entirely dependent on the vast irrigation systems which have been constructed. Only in the extreme north is rain-fed agriculture practised, but only to a limited

[1] This article is based mostly on data collected in the course of the Indus Basin Survey undertaken under the auspices of the International Bank for Reconstruction and Development on behalf of the West Pakistan Government; however, this does not mean that the opinions stated therein necessarily coincide with those of the aforesaid auhorities.

extent. In the months of July, August and September, the whole of the Indus Plain comes under the influence of the monsoon. In this period, heavy and widespread frontal rain storms frequently occur, the intensity of these rainstorms increasing to the north and, to a lesser extent, also to the south. This results in widespread inundation of agricultural land, especially in the north-eastern and southern parts of the Indus Plain, calamities which are aggravated by breaching and overtopping of river bunds due to very high river discharges and inflow of run-off from uphill areas and the Indian Punjab.
It will be clear that a solution of these problems cannot be found only in the construction of storm drains for the discharge of excess rainwater. However, in this paper it will be presumed that sufficient measures are taken to prevent inundation by river water, and to divert inflow from outside areas and only the evacuation of the excess rainfall from the Indus Plain itself will be dealt with.
Except for the Indus and its tributaries, the Indus Plain is not provided with much natural drainage. Therefore the construction of storm drains was started already around 1930. At present several large storm drainage systems exist or are under construction. However, it is generally accepted that most of these systems have a too low capacity and that in large areas new storm drainage systems still have to be constructed. High expenses are involved in the construction of storm drains which are directly related to design capacity. Therefore it will be clear that a decision on this capacity is very important. Up till now design capacities have mainly been based on the experience of Pakistani drainage engineers, although budgetary limitations may also have had an influence.
The purpose of storm drainage is to prevent damage. The damage prevented, expressed in terms of money, forms the benefits of the drains. A quantitative treatment of these benefits can provide the means of bringing this type of drainage out of trial and error planning. Therefore, in this paper, after an analysis of the basic hydrological data, an attempt is made to base the assessment of the design capacity on economic considerations.

2 Analysis of the basic hydrological data

2.1 Rainfall

In the original study the Indus Plain has been subdivided into several zones with various rainfall characteristics. This paper will be confined to one of these, the Lahore zone. The other zones were dealt with in the same way, yielding, however, due to differing rainfall, different results.
The rainfall frequency of Lahore for 24- and 48-hour rainstorms is shown in Fig. 1. It has been shown by Tipton and Kalmbach (1) that 72-hour rainstorms have a total depth which is slightly higher than the 48-hour storms. However, since most or all the increase from the third day will be lost by infiltration, no further consideration will be given to 72-hour storms. The point rainfalls of Fig. 1 will have to be reduced for larger areas. Tipton and Kalmbach (1) calculated these reduction factors which are given in Table 1.

2.2 Run-off

The run-off which is the quantity of water to be drained away from a certain rainstorm, has been computed in accordance with the method derived by the U.S. Soil

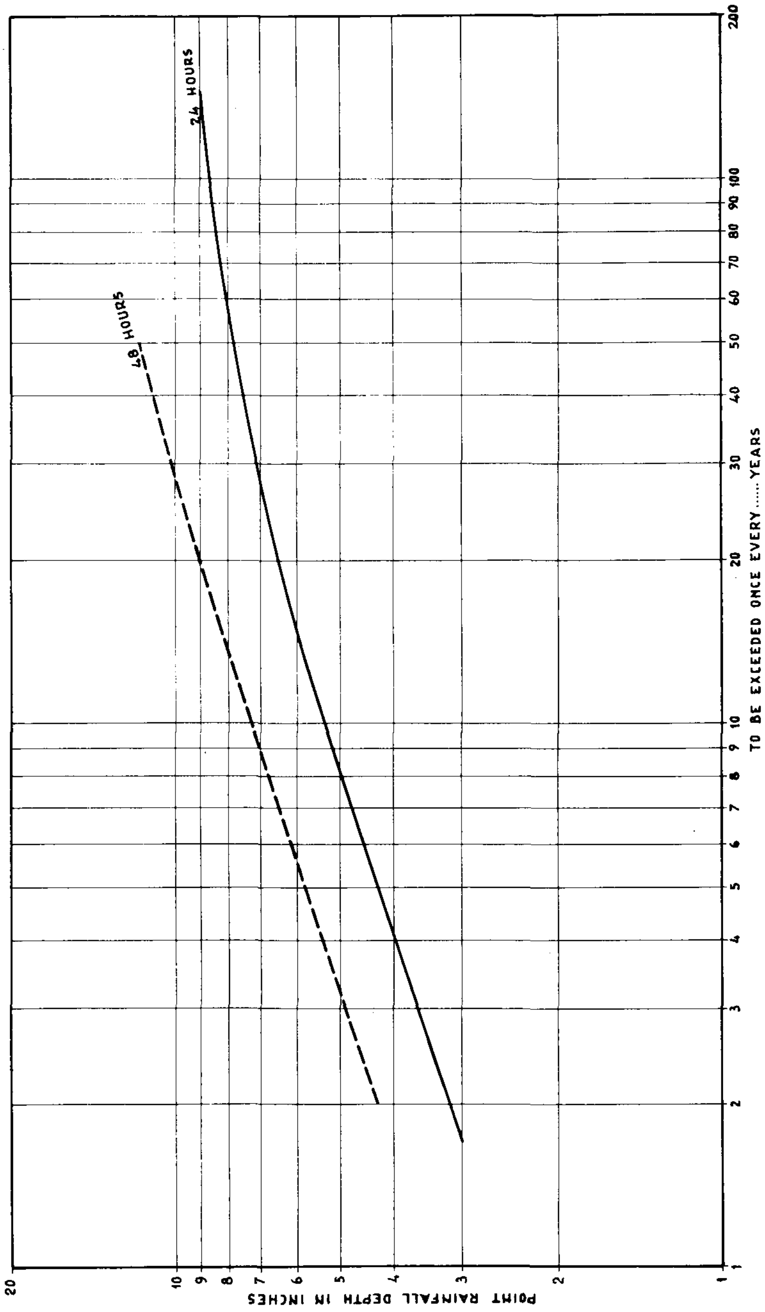

Fig. 1 Rainfall frequency in the Lahore zone.

Table 1 Areal distribution of rainfall in the Northern Indus Plain

Area in square miles	*Percentage of point rainfall over the whole area*
250	89
500	83
750	76

Conservation Service (2) which is based on a number of curves from which the run-off from a certain rainstorm can be read. Tables from which the appropriate curve for the particular circumstances can be assessed are given in the same paper. Based on local observations curve 78 was selected for the first day and curve 93 for the second day. For the sake of convenience these curves have been given in Table 2.
The distribution of the 48-hour rainfall over the two days is unknown. Two calculations have been made based on the arbitrary assumption that a 48-hour rainfall for a certain recurrence interval is built up of the 24-hour rainfall for that particular recurrence interval plus an additional (smaller) amount from the preceding or following day. The first case is more unfavourable than the second. The averages of both results have been used for further calculations. It is recognized that these calculations are only an approximation but no more reliable information was available.

Table 2 Rainfall/run-off relationships

Areal rainfall (inches)	*Run-off (inches)*	
	first day (curve 78)	*second day (curve 93)*
1	0.1	0.5
2	0.5	1.4
3	1.1	2.2
4	1.9	3.2
6	3.6	5.2

2.3 Peakflows

For the calculation of the peakflows the unit hydrograph method has been used. By this method it is also possible to estimate the flow occurring 24 hours later than the peakflow. This flow must be known, as the calculations have to be based on a 48-hour rainstorm.
The usual procedure for establishing a unit hydrograph involves the selection of several historical storms and the analysis of concurrent flow hydrographs at a particular station of the basin. In Pakistan, however, such hydrographs of drainage channels were not available. Therefore it was necessary to transfer known unit hydrographs from a basin of similar characteristics to the ungauged basins of West Pakistan. This was done by Tipton and Kalmbach (1) for the design of cross-structures in the Link Canals which connect the rivers of the Punjab. Their method was also applied for

the purpose of this paper. The results of the calculations are listed in Table 3. The 10-year recurrence interval has been left out of consideration as it appears to be of no interest.

Table 3 Calculated peak flows for an average catchment area (500—750 square miles) in the Lahore zone (cusecs/square mile)

Recurrence period	*Peak flow*
2 years	4
3 years	5
4 years	6
5 years	7

3 Estimation of flood damage to crops with storm drainage systems of different capacities

3.1 Duration of floods

Each of the peakflows shown in Table 3 may be used to design a storm drainage system. However, if the point rainfall for the corresponding recurrence interval is exceeded more or less flooding will occur.

Under conditions as prevailling in the Indus Plain, it is reasonable to assume that, if the flood water has disappeared from the fields within five days, damage to crops will be negligible. Hereafter it will be assumed that the flood waters will be discharged by the drains with the design discharge. In fact, the discharge will tend to be higher but this has not been taken into account as in the Indus Plain the outfall of the drains into the rivers is hampered, to a certain extent, by high water levels in the rivers. Moreover, it will be assumed that evaporation and infiltration are counterbalanced by additional rain. Both assumptions are on the safe side, especially for the longer flooding periods. On the basis of these assumptions the extra point rainfall which can be tolerated above the design point rainfall, can be calculated. For instance, if the design capacity is 4 cusecs/square mile, then in 5 days $5 \times 4 = 20$ cusec days/square mile can be evacuated. This is equal to 0.74 inch/square mile or, as the latter figure represents areal rainfall, to $0.74/0.8 = 0.9$ inches point rainfall. Adding this last figure to the design point rainfall gives the limit at which the point rainfall becomes injurious. This has been done in Table 4.

To arrive at an average annual damage to crops, a certain period has to be considered. For this purpose a period of 50 years has been adopted. The 48-hour point rainfall with a recurrence interval of 50 years is 12 inches (Fig. 1). This rainfall is under average conditions the maximum rainfall to be expected in a future period of 50 years.

Again assuming that floodwater is evacuated with design capacity and that evaporation and infiltration are counterbalanced by additional rain, the flooding period as a result of this maximum rainfall is as shown in Table 5. Although the excess rainfall occurs over the whole catchment area, the periods of flooding calculated in Table 5 are maxima which occur only in the lower areas in the vicinity of the drains. Higher parts of the terrain will be inundated only for a short period or not at all.

Table 4 Damaging 48-hour point rainfalls for different design capacities of storm drainage systems in the Lahore Zone

Recurrence intervals (years)	*Design 48-hour point rainfall (inches)*	*Design capacity (cusecs/sq.mile)*	*Extra point rainfall without damage (inches)*	*Injurious 48-hous point rainfall (inches)*
2	4.3	4	0.9	over 5.2
3	4.9	5	1.2	over 6.1
4	5.4	6	1.4	over 6.8
5	5.8	7	1.6	over 7.4

Table 5 Calculations of periods of flooding after a 48-hour, 50-year recurrence interval (= 12 inches) rainstorm for storm drainage system with different design capacities in the Lahore Zone

Design 48-hour point rainfall (inches)	*Design capacity (cusecs/ sq.mile)*	*Excess point rainfall (inches)*	*Areal rainfall excess*		*Period of flooding*
			(inches)	*(cusec days/ sq.mile)*	
4.3	4	12 — 4.3 = 7.7	0.8 × 7.7 = 6.2	167 [1]	42 [2]
4.9	5	12 — 4.9 = 7.1	0.8 × 7.1 = 5.7	154	31
5.4	6	12 — 5.4 = 6.6	0.8 × 6.6 = 5.3	143	24
5.8	7	12 — 5.8 = 6.2	0.8 × 6.2 = 5.0	135	19

[1] 1 inch × 1 sq.mile = 27 cusec days
[2] 167/4 = 42

3.2 Crop damage

Some crops like rice and sugar-cane can stand flooding rather well and it may be assumed that farmers adapt their cropping pattern in areas where flooding is likely to occur, by planting for instance less cotton and more rice.

Moreover, the assumptions on which the flooding periods have been calculated are rather conservative. Therefore, it has been assumed that after a calculated flooding period of 60 days the yield decrease averaged over all crops will amount to 60 % of the normal yield. It has already been discussed that a flooding period of 5 days does no appreciable harm. It is recognized that these figures are only a rough approximation. In fact, flood damage to crops depends on the cropping pattern, the crop varieties and the growing stage.

The two points mentioned above have been plotted in Fig. 2 and connected by a straight line. This again is an assumption which was made in the absence of factual figures. It was found that the results of the analysis are not too sensitive to this assumption.

With the help of the calculated non-damaging point rainfall, the calculated flooding period for a 48-hour, 50-year recurrence interval rainstorm (12 inches) and Fig. 2, the beginning and the end of the lines of Fig. 3, giving the relation between crop damage and 48-hour point rainfall with drainage systems of different design capacity, can be found. Here too, in the absence of more reliable data, the two points have been connected by a straight line.

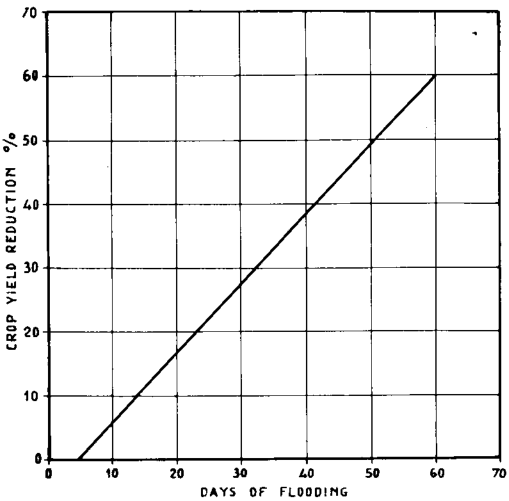

Fig. 2 Estimated crop damage in relation to flooding period.

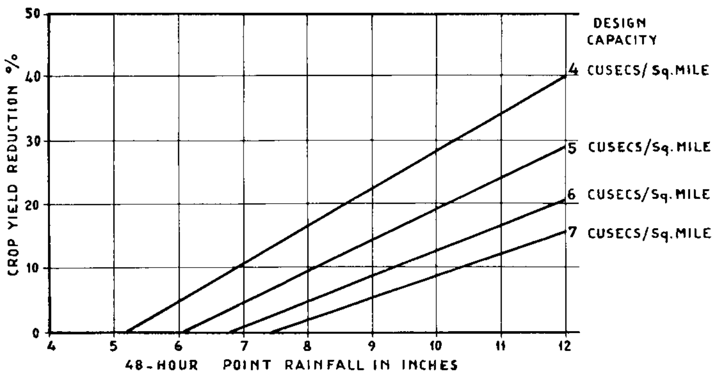

Fig. 3 Estimated crop damage in relation to 48-hour point rainfall with drainage systems of different design capacity.

From the rainfall frequency curve an estimate can be made of the frequency and magnitude of all damaging rainstorms in a future 50-year period. Then, the crop damage can be read from Fig. 3, after which the total and average yearly crop damage for a 50-year period could be calculated. This has been done in Table 6. Average annual crop damage figures for design capacities of 2 and 3 cusecs per square mile could not be calculated in this way. This because in these cases the calculated flooding period would become so long that it would be unreasonable to assume that during the flooding period evaporation and infiltration would be equal to additional rain. The actual flooding period would certainly be much shorter than calculated. Therefore they have been estimated at 10 and 6% respectively. As heavy rain only occurs in the monsoon period (the summer), the figures of Table 6 have only to be applied to summer crops.

Table 6 Estimated total average annual crop damage in % in a 50 year period with drainage systems of different design capacity in the Lahore Zone

48-hour point rainfall		*Design capacity (cusecs/sq.mile)*			
inches	*occurrence in 50 years*	4	5	6	7
12	1	1 × 40 = 40	1 × 29 = 29	1 × 21 = 21	1 × 16 = 16
10	1	1 × 28 = 28	1 × 20 = 20	1 × 13 = 13	1 × 9 = 9
9	1	1 × 23 = 23	1 × 15 = 15	1 × 9 = 9	1 × 6 = 6
8	1	1 × 17 = 17	1 × 10 = 10	1 × 5 = 5	1 × 2 = 2
7.5	1	1 × 14 = 14	1 × 7 = 7	1 × 3 = 3	
7	1	1 × 11 = 11	1 × 5 = 5	1 × 1 = 1	
6.5	1	1 × 8 = 8	1 × 2 = 2		
6	2	2 × 5 = 10			
5.5	6	6 × 2 = 12			
total crop damage in 50 years		163	88	52	33
average annual crop damage		3.3 %	1.8 %	1.0 %	0.7 %

4 Estimates of capital and annual cost of storm drainage system with different design capacities

In West Pakistan the Irrigation Department and the Agricultural Development Corporation have prepared cost estimates for several storm drainage systems to be constructed. These cost estimates expressed in terms of rupees per acre of catchment area showed considerable variation. This is not surprising, as these costs depend on a number of factors such as:

- design capacity (the higher the design capacity, the higher the cost involved);
- the size of the catchment area (in a bigger catchment area relatively more large drains are included, which increases the cost per acre);
- the intensity of the drainage system;
- the number of structures required, which depends largely on topography and infrastructural features, such as roads and irrigation canals which have to be crossed.

For the purpose of this paper only the relation between capital cost and design capacity is of interest. After a study of the data available it was found that the figures as given in Table 7 could serve as a reasonable basis for the general purpose of the study. These estimates are based on an approximate spacing of the lowest order drains of 2 miles. In such a case additional field drains will be required to connect the individual fields of the farmers with the public drainage system. It was assumed that these field drains will be constructed by the farmers themselves, half by family labour, half by hired labour. Only the cost for hired labour, estimated at an average of Rs. 6 per acre will be taken into further consideration. Maintenance of these field drains will be a relatively small job, and no further attention will be paid to it.
Maintenance of the storm drainage comprises maintenance of the inspection roads, weed clearance, repair of minor gullies caused by rain and of damaged inlets, silt

clearance and repair to structures and major breaches. After some model calculations, based on the figures available, the annual cost of maintenance, including operation, was estimated (Table 7).

Table 7 Capital and annual cost of storm drainage systems (Rs/acre)

Design capacity	*Capital cost*	*Annual cost*
2 cusecs/sq.mile	70	0.70
3 ,, ,,	100	0.80
4 ,, ,,	130	0.90
5 ,, ,,	155	0.95
6 ,, ,,	175	1.00

5 Selection of the economically justified design capacity

In the foregoing sections figures on cost and flood damage to crops have been derived for storm drainage systems with various design capacities. In this paragraph the economically justified design capacity will be selected from this range.
For this purpose cost and benefits of storm drainage systems will be expressed in terms of the present value (P.V.) which was calculated with a discount rate of 8 % as per 1965 over a period of 25 years. In other words the amount of money was calculated which, if in hand in 1965, would have been of the same value as all the costs or benefits to be made or gained in the period 1965–1990. These calculations can easily be made with the help of appropriate tables. A discount rate of 8 % is considered to give a reasonable estimate of the opportunity cost of capital.
A marginal analysis would be preferable. However, estimates of cost and benefits for storm drainage systems with various design capacities are not accurate enough to allow for more than a linear interpolation. Therefore, incremental cost and incremental benefits will be compared over intervals of 1 cusec./sq.mile. As long as incremental cost are smaller than incremental benefits, a larger capacity will be selected.
Benefits of storm drainage systems can be expressed in terms of crop damage prevented. The flood damage in paragraph 3 has been expressed in % of the yield of the summer crops. Therefore, the P.V. of the net production value (N.P.V.) of 1 % of the summer crops was calculated, taking into account estimates of increases in yields and cropping intensity and expected changes in the cropping pattern.
The benefits of a storm drainage system do not start at the same time as the construction. The construction period of a large storm drainage system in the Indus Plain is about 3 years. Moreover, it is expected that the required field drains (see paragraph 4) will only gradually be constructed after the completion of the main system. For these reasons the following phasing of the benefits has been assumed:

1st and 2nd year:	0 %	5th year:	80 %
3rd year:	60 %	6th year:	90 %
4th year:	70 %	7th and following years:	100 %

On the basis as shown above the P.V. of 1 % of the N.P.V. of the summer crops in the Lahore zone has been calculated at Rs. 12.6 per acre cultivable area. Taking into account the approximate nature of the basic figures, this figure has been rounded off arbitrarily to Rs. 12 per acre catchment area to allow at the same time for a certain percentage of waste land. For the purpose of demonstration, the benefit-cost analysis will be made for Rs. 10, Rs. 12.5 and Rs. 15 P.V. respectively of 1 % of the N.P.V. of the summer crops per acre catchment area.

For the calculation of the P.V. of the cost for a storm drainage system, the following points have to be considered:

— Phasing of the capital cost. The average construction period of a storm drainage system is about 3 years. Therefore the following phasing of capital cost has been assumed: 1st year: 20 % ; 2nd year: 40 % ; 3rd year: 40 %.
— Farmers' cash expenses for field drains (Rs. 6/acre). It is expected that the need for field drains will only gradually be realized by the farmers. Therefore the phasing of these costs has been estimated at: 4th year: 1/6; 5th year: 1/6; 6th year: 2/6; 7th year: 2/6.
— Annual cost. The cost for maintenance during construction is included in the construction costs. Therefore, annual cost for maintenance and operation starts in the 4th year. Based on the foregoing the P.V. of the cost for storm drainage was calculated. The results are given in Table 8.

The calculation of benefits and incremental benefits in terms of % of the summer crops has been made in Table 9 on the basis of the figures arrived at in Table 6. The average annual flood damage to summer crops without storm drains has been estimated at 25 %. Cost and benefits and incremental cost and benefits in terms of money have been calculated in Table 10. From Table 10 it can be seen that in case

Table 8 P.V. of cost for storm drainage systems with different design capacity

Design capacity (cusecs/sq.mile)	*P.V. (Rs./acre catchment area)*
2	71
3	99
4	126
5	148
6	166

Table 9 Benefits and incremental benefits in % of the summer crops of storm drainage systems in the Lahore Zone

Design capacity (cusecs/sq.mile)	*Benefits*	*Incremental benefits*
0	0	15
2	25 — 10 = 15	4
3	25 — 6 = 19	2.7
4	25 — 3.3 = 21.7	1.5
5	25 — 1.8 = 23.2	0.8
6	25 — 1.0 = 24.0	

Table 10 Cost and benefits and incremental cost and benefits in Rs./acre of storm drainage systems in the Lahore Zone

Design capacity (cusecs./sq.mile)	*Cost*		*Benefit calculation for a P.V. of 1 % of N.P.V. of summer crops (Rs./acre)*					
			10		12.5		15	
	P.V.	*increment*	*P.V.*	*increment*	*P.V.*	*increment*	*P.V.*	*increment*
2	71		150		188		225	
		28		40		50		60
3	99		190		238		285	
		27		27		33		40
4	126		217		271		325	
		22		15		19		23
5	148		232		290		348	
		18		8		10		12
6	166		240		300		360	

of the afore mentioned value of Rs. 12 per acre for the P.V. of 1 % of the N.P.V. of the summer crops the economically justified design capacity is in the order of 4 cusecs/sq.mile. For a larger capacity the incremental cost to be spent is larger than the incremental benefits to be gained. For the sake of convenience, incremental cost and benefits have been graphically presented in Fig. 4, assuming that the incremental cost and benefits between e.g. 2 and 3 cusec/sq.mile are equal to marginal cost and benefits at 2.5 cusec./sq.mile. The unit of both marginal cost and marginal benefits is Rs/acre catchment per cusec./sq.mile. The intersection point of the marginal cost and marginal benefit lines indicates the economically justified design ca-

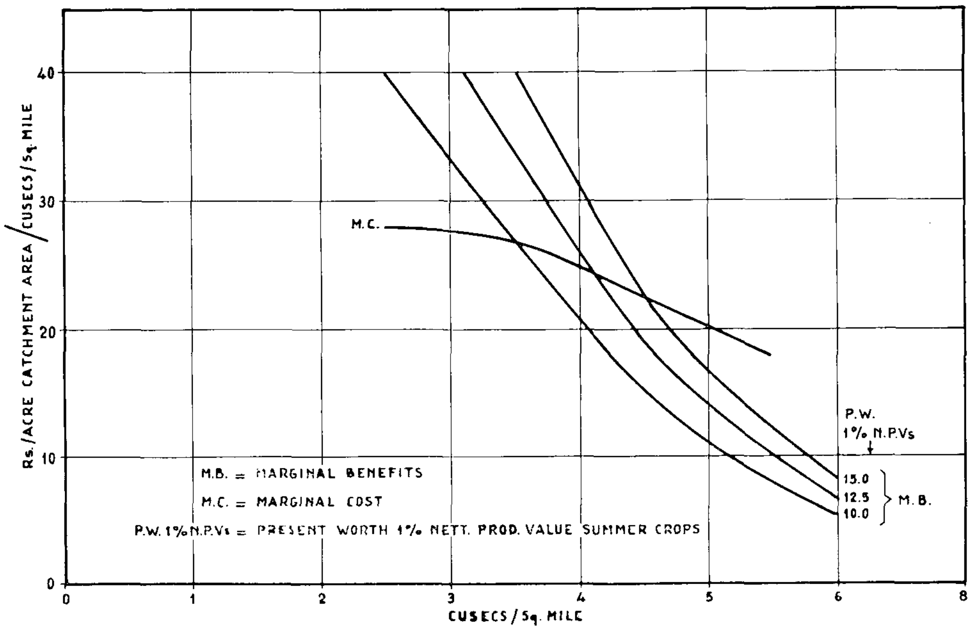

Fig. 4 Marginal costs and marginal benefits of storm drainage systems in the Lahore zone.

pacity. Fig. 4 also shows that a higher standard of agriculture in the area justifies a higher design capacity.

6 Commentary

The aim of this article is mainly to indicate a method for the assessment of the economically justified design capacity of storm drainage systems. Therefore, although many assumptions had to be made, no lengthy explanation of the basis of these assumptions has been given. The assumptions were made to the best of our knowledge, most of them after discussions with other team members.
It would be unduly optimistic to hope that the inaccuracies of the various assumptions have outbalanced each other. Therefore, the result obtained should be considered to be no more than an approximation. The fact that the result does not deviate too much from the opinion of Pakistani drainage engineers which is mainly based on local experience might be mere coincidence.

References

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