PB-224 000

SEDIMENT ROUTING IN IRRIGATION CANAL SYSTEMS

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Prepared for:

Agency for International Development

1973

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BIBLIOGRAPHIC DATA SHEET

1. Report No. 631.7-M215

2.

PB 224 009

3. Report Date 1972(?)

4. Title and Subtitle

"Sediment Routing in Irrigation Canal Systems"

5.

7. Author(s) Khalid Mahmood.

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Colorado State Univ.

10. Project/Task/Work Unit No. 931-17-120-489

11. Contract/Grant No. AID/csd-~~[illegible]~~ 2162

12. Sponsoring Organization Name and Address

Department of State
Agency for International Development
Washington, D.C. 20523

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstracts

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17. Key Words and Document Analysis. 17a. Descriptors

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group 631

18. Availability Statement

19. Security Class (This Report) UNCLASSIFIED

20. Security Class (This Page) UNCLASSIFIED

21. No. of Pages 33

22. Price $2.75

Khalid Mahmood

1905

ASCE National Water Resources Engineering Meeting

January 29, - February 2, 1973 • Washington, D.C. $0.50

SEDIMENT ROUTING IN IRRIGATION CANAL SYSTEMS

Khalid Mahmood, M. ASCE

Meeting Preprint 1905

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SEDIMENT ROUTING IN IRRIGATION CANAL SYSTEMS

by

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ABSTRACT

The routing of bed material load through a branching irrigation canal system in such a way as to insure sediment discharge equilibrium is considered. All the sediment entering the system is disposed of with the water. It is shown that the system equilibrium can be more easily achieved if smaller sediment load concentrations are allocated to irrigation diversions from smaller channels. Also, approximate numerical model for predicting the bed material load from farm turnouts is presented.

INTRODUCTION

The sediment discharge equilibrium of an irrigation canal system requires that in each segment the bed material inflow over a period of time equals the outflow. The bed material outflow from a system consists of the load diverted with irrigation supplies, escape discharges etc. It also includes the bed material mechanically removed from the channels. Stable unlined earth canal reaches can be designed with different bed material transport capacities. However, for such canals, the maximum transport capacities are rather limited because of channel stability considerations. This limitation of stable unlined channels has resulted in the development of extensive sediment exclusion practices

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This study was partly supported by USAID Contract No. AID/csd-2162, Water Management Research in Arid and Sub-Humid Land of the Less Developed Countries with Colorado State University.

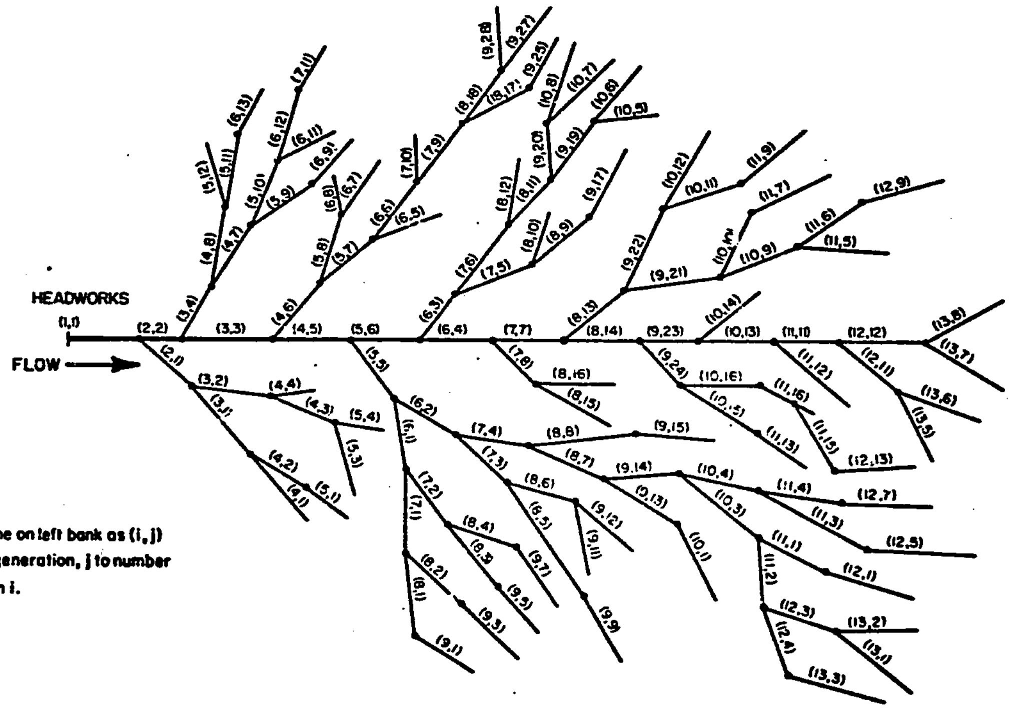
at the headworks of irrigation systems supplied from low head diversion structures on sand-bed channels. In addition to the sediment exclusion measures used at the headworks, it is important to design large canal systems with respect to sediment routing. Otherwise, some channels in the system may lose conveyance capacity due to accumulation of sediment. In fact this accretion of sediments is a serious problem in many existing irrigation systems.

An irrigation canal network with 5,000 cfs discharge capacity at the headworks was simulated by the writer considering sediment discharge equilibrium (1). This network is shown in Fig. 1 and its characteristics are shown in Fig. 2. Herein, the routing of sediment through the system is considered and the goal is to dispose of the incoming sediment load with the water diversions. The distribution of bed material load among the irrigation diversions is also studied for its effect on the system design. Sediment delivery from the distributary channels to the farm watercourses is controlled by turnouts. The sediment withdrawal by turnouts thus forms an important component in routing the bed material load through canal networks. This aspect of turnout design is also considered.

Design of Stable Channel Sections: A number of methods are available for the design of stable channel sections and for computing their bed material transport capacities. For a particular system, the designer should adopt the design procedure best applicable to his conditions. Herein, the design of stable channel sections is based on regime equations as follows:

Section geometry and size functions:

$$f_{vr} = \alpha_1 \sqrt{D_{50}} \qquad (1)$$



1. Channel name on left bank as (i, j)
2. i refers to generation, j to number of channel in i.

Fig. 1 Simulated Irrigation Canal System with 5,000 cfs Discharge at Headworks

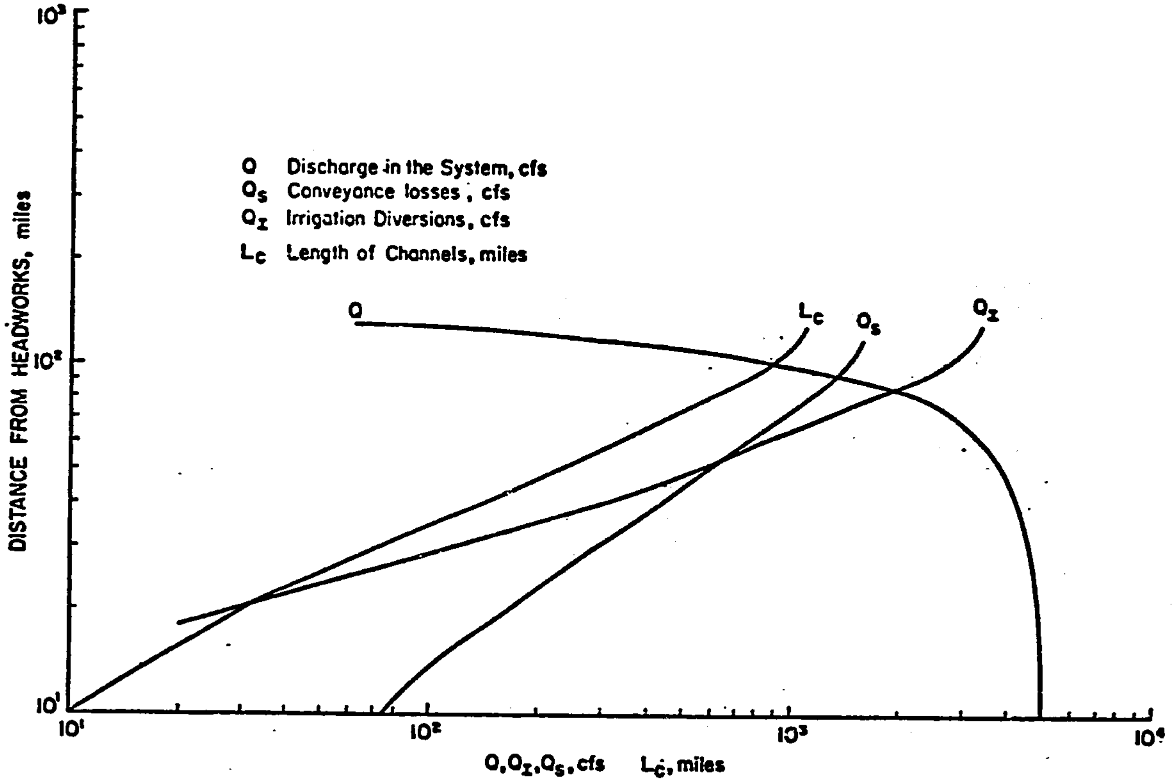


Fig. 2 Discharge and Channel Length Variation with Distance from Headworks in the Simulated System

$$V = \alpha_2 \sqrt{f_{vr} R} \qquad (2)$$

$$P = \alpha_3 \sqrt{Q} \qquad (3)$$

Resistance functions:

$$f_{sq} = \alpha_4 f_{vr}$$

$$S = \frac{5.47 \times 10^{-4}}{Q^{1/6}} f_{sq}^{5/3} \qquad (5)$$

In Eqs. (1) through (5), f is the silt factor, D_{50} is the median bed material size, R is the hydraulic mean radius of the channel section, P is the wetted perimeter, Q is the discharge and S is the energy gradient. All these quantities are conventionally expressed in fps units except D_{50} which is in millimeters. The subscripts used with f denote the value of silt factor that is to be used in the two sets of equations.

In the application of regime equations, coefficients α_1, α_2, α_3 and α_4 show larger variations among different systems than the power indices in the equations. These variables are called the "regime coefficients." A canal system in which all the channels have been designed with similar values of regime coefficients is called a system with "regime similarity."

The computations of bed material transport have been based on the method developed by the writer (2). As the transport quantities are used herein mostly in terms of ratios rather than absolute numbers, the overall conclusions would remain valid, if a different bed material transport equation was used.

The object of sediment routing in an irrigation canal system is to distribute the total bed material load among different channels and water diversions based on the continuity of sediment mass. However, in distributing the sediment load among channels and farm units with different discharges, the equitability of sediment load can be better judged on the basis of concentration rather than absolute magnitudes of sediment loads. For this reason, the system design parameters are expressed herein in terms of bed material load concentration.

BED MATERIAL TRANSPORT CAPACITY

In the design of irrigation canal networks that transport and distribute the incoming bed material load with the water supply, it is necessary to consider:

(1) the distribution of bed material load among irrigation diversions;

(2) the variation of the required transport capacity in the system as a result of (1), and

(3) the possibility of designing unlined stable canal sections that can satisfy the requirements of (2).

The concentration of bed material load allocated to an irrigation diversion in the system should be governed by the capacity of the land to accommodate the sediment load without deteriorating its quality. For example, sandy soils may deteriorate if large quantities of sand size sediments are continuously added with the irrigation supplies. Another consideration should be the bed material transport capacity of the water course channel leading to the farm. For the turnouts in the system that are not critically effected by the preceding considerations, an effort should be made to provide a nearly equal concentration of bed material load. Otherwise, the delivery systems of some farms will suffer aggradation due to higher sediment loads.

For sediment discharge equilibrium, the average bed material load concentration, $\overline{C}_I$ (ppm) in the irrigation diversions from a canal system is

$$\overline{C}_I = \frac{C(1,1)}{(1 - \frac{s}{100})} \qquad (6)$$

where C(1,1) is the bed material load concentration at the head of the system and s is the percentage of discharge consumed in conveyance losses within the system. For the simulated system (Fig. 1), $s = 32.2$ percent and $\overline{C}_I = 1.47\ C(1,1)$.

The proportion of total discharge consumed in conveyance losses increases along the system (refer Fig. 2). The effect of maintaining equal sediment load concentrations in all the irrigation diversions is, therefore, to increase the average bed material load concentration $\overline{C}$ in the channels with increasing distance from the headworks. For the simulated system this increase in concentration with distance from the headworks is illustrated by curve 0 in Fig. 3. In this figure, the required $\overline{C}/C(1,1)$, for providing equal C_I in all the irrigation diversions, is plotted against the distance from the system headworks. It is seen that the remaining discharge in the system is required to transport 1.08, 1.20 and 1.30 times C(1,1) at the 5th, 10th and 12th bifurcation points.

In a bifurcating system of alluvial channels, the average bed material load concentration, $\overline{C}$, generally decreases with an increasing frequency of bifurcations. Consider a system of bifurcating channels with a constant total discharge Q and bed material size, D_{50} throughout the system. If the channels have regime similarity, the bed material load concentration, $C(i)$ for a channel in the system can be expressed as a power function of the channel discharge, $q(i)$, i.e., $C(i) \propto \{q(i)\}^{a}; a > 0$. The ratio of bed material transport capacity $GH(1)$ at the head of the system and $GH(i)$, lower down where Q has been divided into n channels is given by

$$\frac{GH(i)}{GH(1)} = \frac{\sum_{j=1}^{n} (q_j^{1+a})}{[\sum_{j=1}^{n} q_j = Q]^{1+a}} \leq 1 \qquad (7)$$

or

$$\frac{\overline{C}}{C(1,1)} \leq 1 . \qquad (8)$$

In bifurcating irrigation networks, the ratio $\overline{C}/C(1,1)$ decreases with increasing distance from the headworks on account of:

(1) decreasing quantity of discharge remaining in the system and

(2) the division of discharge into a number of channels.

The variation of $\overline{C}/C(1,1)$ along the simulated system is shown by Curve I in Fig. 3. This is based on a regime similarity design of channels in the network with regime coefficients $\alpha_1 = 1.76$, $\alpha_2 = 1.15$, $\alpha_3 = 2.67$, $\alpha_4 = 1.10$ and with a constant $D_{50} = 0.25$ mm. Comparison of curves 0 and I in Fig. 3 shows that for a constant C_I and D_{50} in the system and with the channels designed for regime similarly, it is not possible to satisfy the required distribution of $\overline{C}$ in the system. In actual irrigation systems, the bed material size reduces with distance in the system. Therefore, the transport capacity of the

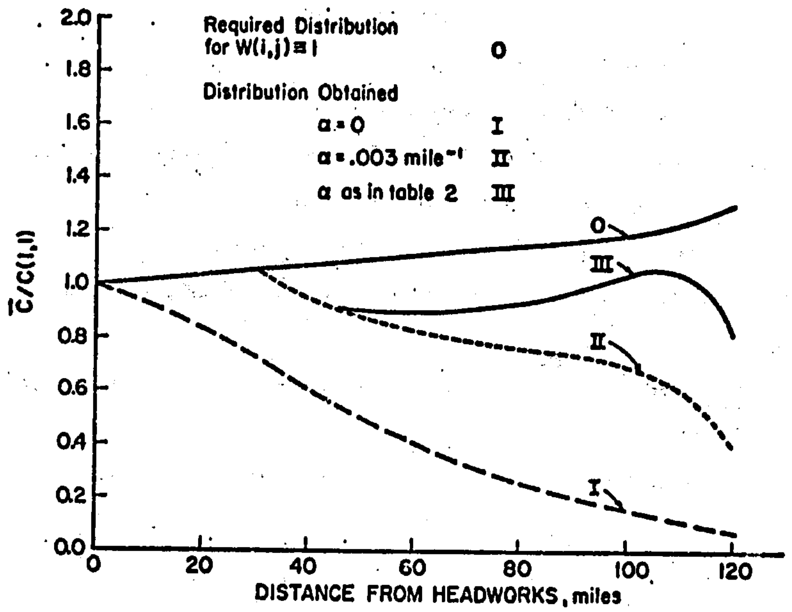


Fig. 3 Variation of Average Bed Material Load Concentration, $\bar{C}$ in the Simulated System (Channels Designed for Regime Similarity)

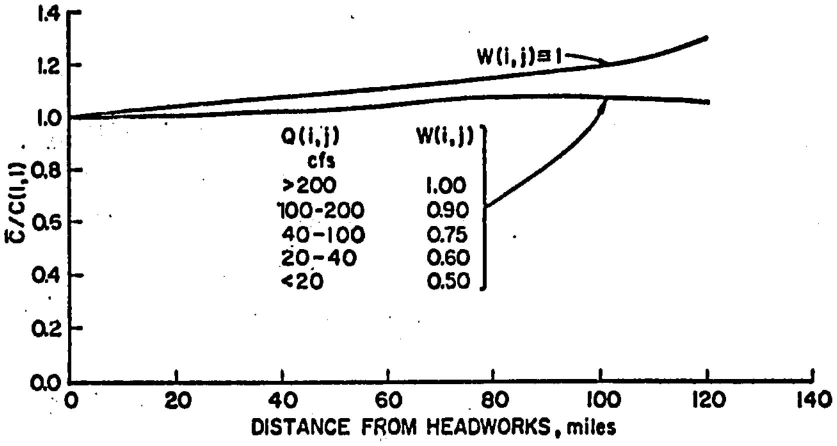


Fig. 4 Effect of Weight Factors, W(i,j) on the Required Average Bed Material Load Concentration in the Simulated System

middle and lower reaches of the system would be greater than that indicated by Curve I in Fig. 3. Curves II and III in this figure represent values of $\bar{C}/C(1,1)$ obtained in the system for different magnitudes of bed material size reduction along the direction of flow. This aspect of system design is discussed later.

To overcome the discrepancy between the required (Curve 0) and the derived distributions (Curves I, II or III) of $\bar{C}/C(1,1)$ in the system, it is necessary to either

(1) increase the bed material load transport capacity of the system in the middle and lower reaches, or

(2) decrease the bed material load allocations to the irrigation diversions from the lower reaches of the system, or

(3) allow sediment to accumulate in the middle and lower reaches of the system and periodically remove it by bed clearance.

A combination of two or all the methods can also be adopted in a system. For these conditions, the distribution of bed material load in the channels and their irrigation diversions can be calculated as follows.

Sediment load distribution:

Let the irrigation diversions $Q_I(i,j)$ from channel $CH(i,j)$ draw bed material load concentrations $C_I(i,j)$ in proportion to some non-negative weighting factor $W(i,j)$. Also for $CH(i,j)$, let $Q_s(i,j)$ = seepage loss in cfs, $Q_b(i,j)$ = average loss in cfs due to accidents and escapages, $C_b(i,j)$ = bed material load concentrations of $Q_b(i,j)$ in ppm and $G_c(i,j)$ = average quantity of bed material removed by bed clearance in lbs. per second. Then the total discharge $Q(i,j)$ in cfs, bed material load $G(i,j)$ in lbs. per second and its concentration $C(i,j)$ in ppm at the head of $CH(i,j)$ are given by

$$Q(i,j) = \sum_{k,l \in N} \{Q_I(k,l) + Q_s(k,l) + Q_b(k,l)\} ,$$

$$G(i,j) = \sum_{k,l \in N} \{Q_I(k,l) \cdot C_I(k,l) + Q_b(k,l) \cdot C_b(k,l)\} \; 62.5 \times 10^{-6} + \sum_{k,l \in N} G_c(k,l)$$

and

$$C(i,j) = \frac{G(i,j) \cdot 10^{+6}}{62.5 \; Q(i,j)} ,$$

where the summation for k and l is over the subset N of the channels in the system that include all the channels supplied by and including $CH(i,j)$.

For the total system:

Irrigation discharge,

$$TQ_I = \sum_{\substack{i=1,n \\ j=1,m}} Q_I(i,j) = Q(1,1) - \sum_{\substack{i=1,n \\ j=1,m}} \{Q_s(i,j) + Q_b(i,j)\}$$

$$= Q(1,1)\left(1 - \frac{s}{100}\right),$$

weighted irrigation discharge, $WQ_I = \sum_{\substack{i=1,n \\ j=1,m}} Q_I(i,j) \cdot W(i,j)$,

bed material load diverted with TQ_I ,

$$TG_I = G(1,1) - \sum_{\substack{i=1,n \\ j=1,m}} Q_b(i,j) \cdot C_b(i,j) \; 62.5 \times 10^{-6} - \sum_{\substack{i=1,n \\ j=1,m}} G_c(i,j)$$

$$= G(1,1)\left(1 - \frac{g}{100}\right).$$

For individual channel segments,

$$C_I(i,j) = C(1,1) \cdot \frac{\left(1 - \frac{g}{100}\right)}{\left(1 - \frac{s}{100}\right)} \cdot \frac{TQ_I}{WQ_I} \cdot W(i,j).$$

The parameters that need to be considered for the distribution of bed material load in the system are:

(1) the ratio of the bed material load concentration in CH(i,j) to that at the head of the system,

$$C_r(i,j) = \frac{C(i,j)}{C(1,1)}$$

(2) the ratio of bed material load concentration in irrigation supplies from CH(i,j) to C(1,1),

$$C_{I_r}(i,j) = \frac{C_I(i,j)}{C(1,1)}$$

and (3) the ratio of the bed material load concentration in the irrigation supplies from CH(i,j) to the concentration in the channel, C(i,j),

$$C_{rat}(i,j) = C_I(i,j)/C(i,j) .$$

The distribution of C_r within the system denotes the relative sediment transport capacity required for various channels in the system. The distribution of C_{I_r} denotes the departure of C_I in various channels from the average value of C_I in the system with $g = 0$ (i.e. $\overline{C}_I$ in Eq. 6). Parameter C_{rat} is important in designing the farm turnouts in a channel segment. It is discussed later.

For a system of weighting factors W(i,j) , that allocates smaller C_I to the diversions from smaller channels as

$Q(i,j)_{cfs}$	W(i,j)
> 200	1.00
100 - 200	0.90
40 - 100	0.75
20 - 40	0.60
< 20	0.50

the variation of required $\bar{C}/C(1,1)$ is shown in Fig. 4 along with the condition for $W(i,j) \equiv 1$.

The values of sediment distribution parameters for three contiguous channel segments are given in table 1 for the preceding values of $W(i,j)$. For comparison, the values of these parameters are also given for $W(i,j) \equiv 1$. It is seen that with unequal values of $W(i,j)$, the maximum values of C_r in the system are reduced. This can be an important advantage in designing unlined stable channel sections in the system, because of their limited bed material transport capacities.

BED MATERIAL SIZE VARIATION

A common characteristic of the drainage and irrigation channel networks is the reduction of bed material size along the channels. This size reduction has a significant effect on the bed material transport capacity and on the morphology of the channels in the system. In large systems, the bed material size reduction along the channels should be considered if meaningful results are to be obtained.

The bed material samples in sand-bed channels obtained with scoop type samplers (US BMH-60 or US BM-54) are more representative of the particle size distribution near the bed surface. The size distribution at the bed surface is appreciably effected by the location of the sampling point with respect to the bed form (3), the wash load present in the flow (4), and possibly by the presence of transverse bars (5). For these reasons, surface samples of bed material in sand bed canals show a large variation in size from one sample to another as well as from one sampling point to another. Therefore, the bed material size reduction does not appear as a continuous process along

TABLE 1

EFFECT OF W(i,j) ON THE SEDIMENT LOAD DISTRIBUTION PARAMETERS IN THE SIMULATED SYSTEM

CHANNEL (i,j)	DISCHARGE AT HEAD cfs Q(i,j)	C_r		C_{I_r}		C_{rat}	
		1*	2*	1*	2*	1*	2*
			CHANNEL A				
1,1	5,000	1.00	1.00	0.00	0.00	0.00	0.00
2,2	4,590	1.01	1.01	0.00	0.00	0.00	0.00
3,3	4,090	1.01	1.01	0.00	0.00	0.00	0.00
4,5	3,530	1.02	1.02	0.00	0.00	0.00	0.00
5,6	1,940	1.04	1.04	1.47	1.91	1.42	1.83
6,4	1,370	1.05	1.06	1.47	1.91	1.40	1.81
7,7	1,230	1.07	1.08	1.47	1.91	1.38	1.76
8,14	743	1.09	1.10	1.47	1.91	1.36	1.74
9,23	446	1.11	1.13	1.47	1.91	1.34	1.69
10,13	357	1.13	1.14	1.47	1.91	1.31	1.66
11,11	271	1.15	1.17	1.47	1.91	1.28	1.63
12,12	117	1.20	1.16	1.47	1.72	1.23	1.48
13,7	42	1.26	1.22	1.47	1.43	1.17	1.17
			CHANNEL B				
4,6	497	1.10	1.10	1.47	1.91	1.35	1.74
5,7	352	1.11	1.10	1.47	1.91	1.33	1.74
6,6	265	1.13	1.10	1.47	1.91	1.31	1.73
7,9	204	1.16	1.10	1.47	1.91	1.27	1.74
8,18	96	1.21	1.02	1.47	1.43	1.22	1.39
9,27	32	1.29	1.00	1.47	1.15	1.15	1.15
			CHANNEL C				
5,5	1,530	1.04	1.03	1.47	1.91	1.42	1.84
6,2	1,060	1.05	1.04	1.47	1.91	1.41	1.83
7,4	756	1.05	1.02	1.47	1.91	1.40	1.86
8,7	636	1.07	1.04	1.47	1.91	1.37	1.83
9,14	514	1.11	1.06	1.47	1.91	1.34	1.80
10,3	320	1.13	1.08	1.47	1.91	1.31	1.78
11,2	195	1.16	1.06	1.47	1.72	1.27	1.61
12,3	99	1.21	1.02	1.47	1.43	1.22	1.40
13,1	31	1.29	1.00	1.47	1.15	1.15	1.15

*1. $W(i,j) \equiv 1$ in the system.
*2. $W(i,j)$ as given on page 9.

the channel length. However, the general trend of decreasing bed material size along the flow is apparent, as shown by the analysis of canal and river data (6).

There are two major factors responsible for the reduction of bed material size in sand-bed irrigation canal networks; one is related to the transport phenomenon and the other pertains to the design of turnout and bifurcation structures.

The median size of the bed material transported by flow in sand-bed channels is generally smaller than the median size of the bed material (7). Thus if a sand-bed channel forms its bed by transporting material from upstream, the bed material size will reduce with distance in the downstream direction. This type of size reduction has been documented (6) and analyzed (8). In irrigation canals, the original bed material is determined by the soil profile traversed by the channels. In time, as the systems are operated, the bed material at each section tends to the size of load transported from upstream (9).

The design of bifurcation structures and irrigation turnouts also effects the variation of bed material size along an irrigation system. Under equilibrium flow conditions, both the concentration and median size of the transported bed material increase from water surface to the bed of the channel. In general, an off take or a farm turnout that draws more than the average concentration in the parent channel also draws greater amount of coarser fractions of bed material load. The farm turnouts are specially designed to conduct larger bed material concentrations than that transported in the parent channels. Consequently the turnouts in irrigation channels enhance the rate of decrease of channel bed material size in the direction of flow.

The bed material size reduction in alluvial channels is generally represented as:

$$D_{50_\ell} = D_{50_o} e^{-\alpha L} \quad (7)$$

where subscripts o and ℓ refer to the initial section and another section at distance L downstream and α is a constant for a given channel reach. Values of α for existing channels can be determined by regression of $\ell n[D_{50}]$ on distance L. For design purposes there is no rational procedure for predicting α . However, the preceding qualitative discussion combined with experience on similar systems does provide a guide for estimating the design values of α . In general the value of α is smaller in large channels than in small channels. It is also smaller in channels with smaller rates of irrigation diversions per unit length, on account of the sediment withdrawal characteristics of the farm turnout.

To illustrate the effect of α on the bed material transport capacity of the system, the channels were designed for regime similarity with $\alpha_1 = 1.76$, $\alpha_2 = 1.15$, $\alpha_3 = 2.67$ and $\alpha_4 = 1.10$. The bed material size at head of the system was assumed as 0.25 mm. Figure 3 shows the variation of $\bar{C}/C(1,1)$ for different values of α . Curve III in the figure corresponds to α values that are inversely related to channel discharge (table 2). These values are representative of similar field systems with $C(1,1)$ up to 150 ppm.

TABLE 2

Q cfs	$\alpha_{\text{mile}^{-1}}$
>2,500	0.0030
1,250 - 2,500	0.0035
500 - 1,250	0.0040
50 - 500	0.0045
<50	0.0055

DISCHARGE OF SEDIMENT THROUGH FARM TURNOUTS

The withdrawal of bed material load with the irrigation diversions from a system is an important consideration in achieving a sediment discharge balance. The farm diversions are made through turnouts in the canal and the water is delivered to the farm through smaller water course channels. The operation of turnouts in an irrigation network can vary from "continuous" to "on-demand." The policy regarding the adjustment of turnout opening and discharge also varies with the organization of the system. In countries such as Pakistan, the discharge through turnouts cannot be adjusted to demand and the turnouts are of a continuous operation type. In the United States, most irrigation projects have adjustable turnouts that are operated on a "continuous" to "on-demand" basis. The design of the turnout in an irrigation system largely depends on the type of operation envisaged in the project. For continuous operation, nonadjustable type turnouts, the design of turnouts further depends on the possible variations in the canal water levels. Where these variations are large, say from season to season, the turnouts are set closer to the channel bed to dampen their effect on the turnout discharge. In such cases the turnouts are generally of an orifice type. The crest levels of the turnouts are mostly set close to the channel bed so they can draw water during periods of low flow in the canals.

Bed material load withdrawal by farm turnouts is difficult to treat analytically. An approximate numerical model of sediment withdrawal by an orifice type turnout has been developed by the writer. In this model, the turnout is replaced by a uniformly distributed sink and the flow field of this sink is kinematically superimposed on the channel flow. From the resulting flow field, a region in the channel, beyond the influence of the turnout, is determined so that all the flow in this region enters the turnout. This approach is approximately valid, if the local acceleration of flow in the channel, due to the turnout is small. This condition is generally satisfied if the turnout discharge is small compared to the discharge intensity per unit width in the channel. The formulation and use of this method is described in Appendix III. Use of the method is illustrated for the turnouts in CH(11,11) of the simulated system.

Channel data

Discharge, $Q = 271$ cfs

Average velocity, $V = 1.82$ fps

Depth, $d = 4.03$ ft

Average width, $B = 37.0$ ft

Energy gradient $= 1.24 \times 10^{-4}$

Bed material, $D_{50} = 0.174$ mm

Gradation coefficient, $\sigma = 1.35$

Bed material load, $C = 110$ ppm

Turnout data

Size $b = 0.5$ ft

$h = 0.5$ ft

Setting $y_t = (\frac{1-d_c}{d}) = 0.97, 0.85, 0.65, 0.40$

Discharge $Q_t = 3.5, 2.5, 1.5$ cfs

Using the average velocity profiles in alluvial channels (2), and omitting the velocity reduction close to the walls, the boundaries of regions in uniform flow that feed the turnout are shown in Fig. 5. The average bed material load concentration and the particle size distribution of the load in these regions are computed from equilibrium concentration profiles (2). These are presented in Fig. 6 as ratios C_{rat}, D_{50_r} and σ_r of the corresponding quantities between the sediment load entering the turnouts and that transported in the channel. The curves in Fig. 6 can be used to design the turnouts in CH(11,11). For example, if a turnout is to draw 1.4 times the bed material load concentration in this channel, it should have a setting $y_t = 0.86$ or the height of turnout crest above channel bed level, $d_c = 0.56$ ft.

SEDIMENT TRANSPORT IN WATERCOURSE CHANNELS

In a canal system that distributes its sediment load with its water diversions, the most critical component is the transport of sediment in the farm water course channels. The watercourses, leading from turnouts to the farms are small channels with 1.0 - 5.0 cfs discharge. For unlined watercourses, with flat slopes, the bed material transport capacity is rather limited. The physical maintenance of watercourse channels is also poorer than the larger distributary channels and this reduces their transport capacity further.

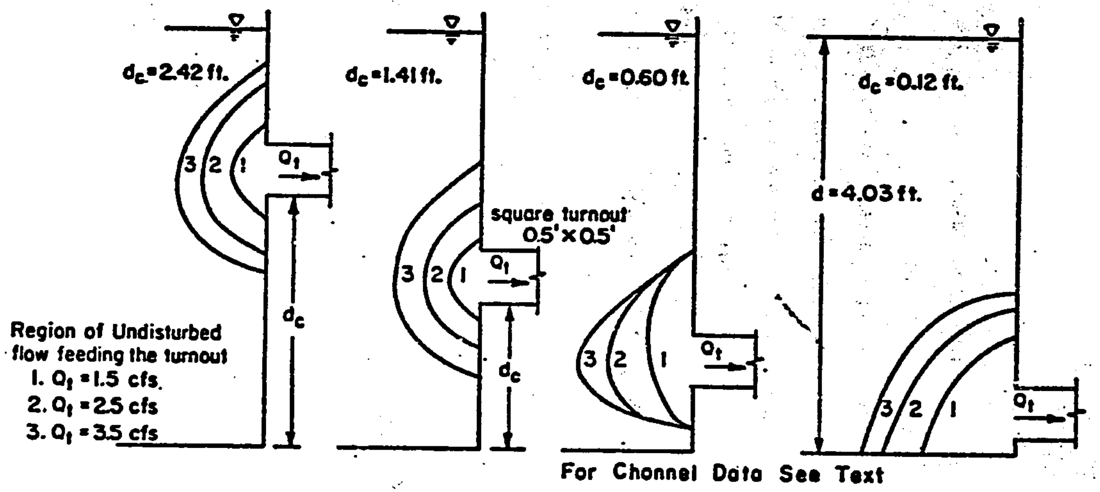


Fig. 5 Regions of Undisturbed Channel Flow Feeding the Turnout for Different Turnout Settings and Discharges in Channel (11,11)

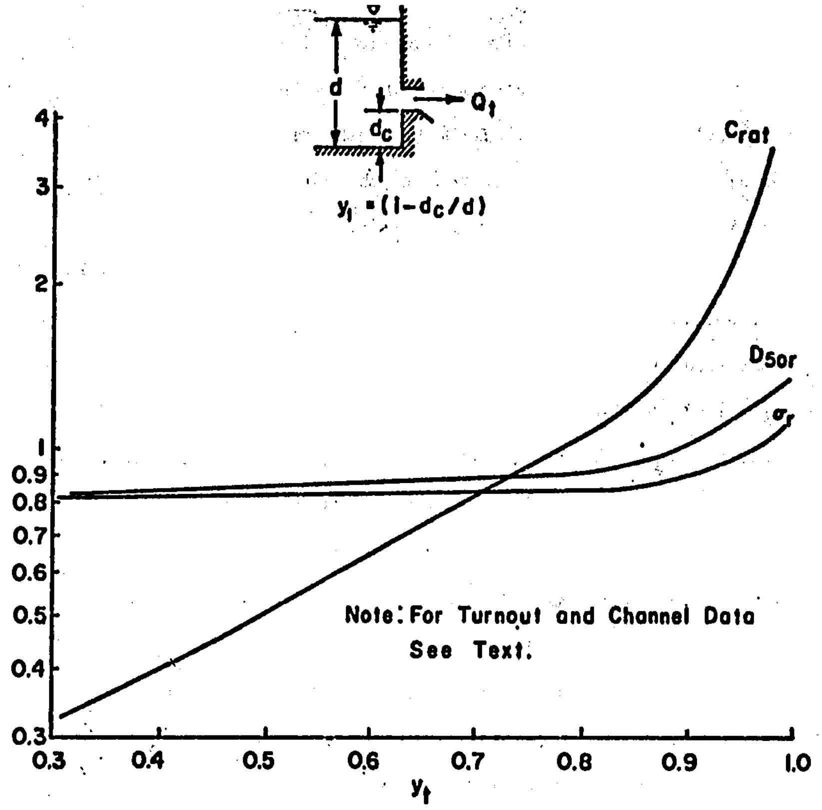


Fig. 6 Variation of Bed Material Load Characteristics of Turnouts on Channel (11,11) With Turnout Setting y_t

The watercourse channels are more susceptible to vegetation and weed growth. During cleaning, the spoil from the bed is often dumped on the banks. This is a source of additional load especially during rain and windstorms. The water level in the watercourse channels is also controlled by the level of the farm being irrigated and the method of irrigation. The flow conditions in the watercourses are frequently nonuniform. Thus the bed material transport in these channels is mostly unsteady, with the channels aggrading under back water conditions.

The equilibrium of sediment discharge in watercourses also requires that the total bed material inflow be balanced by outflow and periodic cleaning. In the design of watercourses, this balance should be achieved for the most critical operational conditions.

The scale of flow in watercourse channels is of the order of the laboratory flume studies. The bed resistance and sediment transport functions obtained from laboratory studies (2, 6, 10, 11 among others can therefore be applied to watercourse channels with greater confidence. However, in computing the overall resistance to flow, the bank resistance should be provided to compensate for future maintenance conditions..

CONCLUSION

In large irrigation canal networks, the disposal of sediments should be properly planned. This planning requires a policy for sediment disposal with the irrigation supplies, bed clearance etc. In systems that are designed to dispose of all the incoming sediment with the irrigation diversion, it is necessary insofar as it is possible to design the sediment transport capacity of the channels to the sediment load imposed by routing.

Routing studies on a simulated network show that a comparatively smaller sediment load allocation to irrigation diversions from smaller channel facilitates the design of the system. The bed material size reduction in alluvial channels has a significant effect on the sediment routing through the system. The size reduction coefficient α, may have to be estimated by experience on similar systems.

An approximate numerical model for predicting the water and sediment discharge through farm turnouts has been presented. This method can be used for analyzing the sediment flow from the canals through small turnouts to the watercourse channels supplying the farms.

In sediment routing through a canal network system, the problem of bed material transport becomes more critical as smaller channels are approached. This problem is most critical in farm watercourse channels that are supplied by the system. The overall sediment disposal capacity of an irrigation system is therefore fixed by the capacity of the farm watercourses rather than by the larger conveyance channels in the system.

The analyses reported herein are based on steady, equilibrium design flows. In the design of sediment routing through a field system, the flow and sediment inflow hydrographs can be similarly treated.

Acknowledgements: This study was partly supported by US AID Contract No. AID/CSd-2162, Water Management Research in Arid and Sub-Humid Land of the Less Developed Countires with Colorado State University. The writer thanks Daryl B. Simon, Associate Dean for Research, Colorado State University for his review of this paper and his helpful suggestions.

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APPENDIX II. - NOTATION

The following symbols are used in this paper.

b,h	Height and width of rectangular orifice turnout
$\bar{C}$	Average value of C at a specified distance from the headworks
C_I	Bed material load concentration in the irrigation supplies from a channel
$\bar{C}_I$	Average value of C_I in the system
$C_{I_r}(i,j)$	Ratio $C_I(i,j)/C(1,1)$
$C_{rat}(i,j)$	Ratio $C_I(i,j)/C(i,j)$
$C(i,j)$	Bed material load concentration in channel (i,j)
$C_r(i,j)$	Ratio $C(i,j)/C(1,1)$
CH(i,j)	jth channel at ith bifurcation in the system
D_{50}	Median bed material size
d	Depth
d_c	Height of crest of turnout above channel bed
f	Lacey's silt factor, subscripts vr and sq refer to the equation in which f is used
G(i,j)	Bed material load at head of CH(i,j)
GH(i)	Total bed material load at the head of channels at bifurcation i
L	Distance along a channel
m	Strength of uniformly distributed sink
P	Wetted perimeter
P(x,y,z)	Point at coordinates x,y,z, in cartesian system
Q	Discharge
$Q_I(i,j)$ $Q_s(i,j)$, $Q_b(i,j)$	Irrigation, seepage and escape discharge from a channel, respectively

Q_t	Turnout discharge
R	Hydraulic mean radius
S	Energy gradient
s	Percentage of total discharge consumed in conveyance losses within the system
TQ_I, WQ_I	Total and weighted total irrigation discharge
u,v,w	Velocity components along x,y,z directions, respectively
V	Average velocity
W(i,j)	Weightage factor for bed material load concentration in irrigation supplies from CH(i,j)
y_t	Setting of turnout $(\frac{1-d_c}{d})$
α	Bed material size reduction coefficient
$\alpha_1, \alpha_2, \alpha_3, \alpha_4,$	Regime coefficients.
σ	Gradation of bed material

APPENDIX III

NUMERICAL MODEL FOR DETERMINING SEDIMENT WITHDRAWAL IN ORIFICE TURNOUTS

Flow Field Due to Distributed Sinks

A uniformly distributed sink of dimensions b x h ft and located in X-Y plane is shown in Fig. 8. The center of this sink is located at (x_o, y_o, o) and its discharge is equal to mbh cfs. At any point P(x,y,z), the components of velocity due to this sink, u_s, v_s and w_s along x, y and z directions are given by:

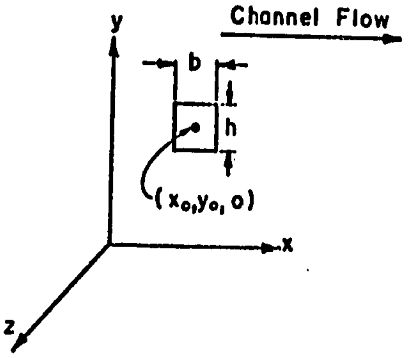

Fig. 7 Uniformly Distributed Sink Representing Turnout

$$u_s = \frac{m}{4\pi} \ \ell n \left(\frac{y_2 + R_{12}}{y_1 + R_{11}} \cdot \frac{y_1 + R_{21}}{y_2 + R_{22}} \right) \qquad (8)$$

$$v_s = \frac{m}{4\pi} \ \ell n \left(\frac{x_2 + R_{21}}{x_2 + R_{22}} \cdot \frac{x_1 + R_{12}}{x_1 + R_{11}} \right) \qquad (9)$$

$$w_s = \frac{m}{4\pi} \ \{ \arctan \frac{Y_1 \cdot X_1}{Z \cdot R_{11}} - \arctan \frac{Y_1 \cdot X_2}{Z \cdot R_{21}}$$

$$+ \arctan \frac{Y_2 \cdot X_2}{Z \cdot R_{22}} - \arctan \frac{Y_2 \cdot X_1}{Z \cdot R_{12}} \qquad (10)$$

where $x_1 = X + \frac{b}{2}$;

$x_2 = x - \frac{b}{2}$;

$y_1 = y - y_o + \frac{h}{2}$;

$y_2 = y - y_o - \frac{h}{2}$;

and $R_{ij} = \sqrt{X_i^2 + Y_j^2 + Z^2}$

To represent the velocity field due to an orifice type turnout by a uniformly distributed sink, it is necessary to satisfy the boundary conditions imposed by the channel geometry. These conditions are: at the water surface and the channel bed, $v_s = 0$; at the channel walls except through the turnout $w_s = 0$. The method of images can be used to satisfy these boundary conditions exactly at two surfaces bounding the channel flow and asymptotically at the two remaining surfaces. The arrangement shown in Fig. 8 exactly satisfies the boundary conditions at the channel wall containing the turnout and the channel bed. The boundary conditions at the water surface can be asymptotically satisfied by increasing the number of images j in the X-Y plane and the boundary conditions at the farther wall of the channel by increasing the number of images in the Y-Z plane.

Superimposition of flow fields:

The flow field due to the sinks is kinematically superimposed on the flow field u_c , v_c and w_c in the channel. The resulting velocity components at a point $P(x,y,z)$ in the channel are:

$$u_p = u_s + u_c$$
$$v_p = v_s + v_c$$
$$w_p = w_s + w_c$$

In the undisturbed region of the channel flow u_c is a function of y and z and $v_c = w_c = 0$.

It is assumed that at $x = x_u$, the flow in the channel is uneffected by the turnout. Starting with different points (y_i , z_i) in the Y-Z plane at $x = x_u$, the path lines are traced up to the Y-Z plane at $x = x_l$. The location of the particle at $x = x_\ell$ is

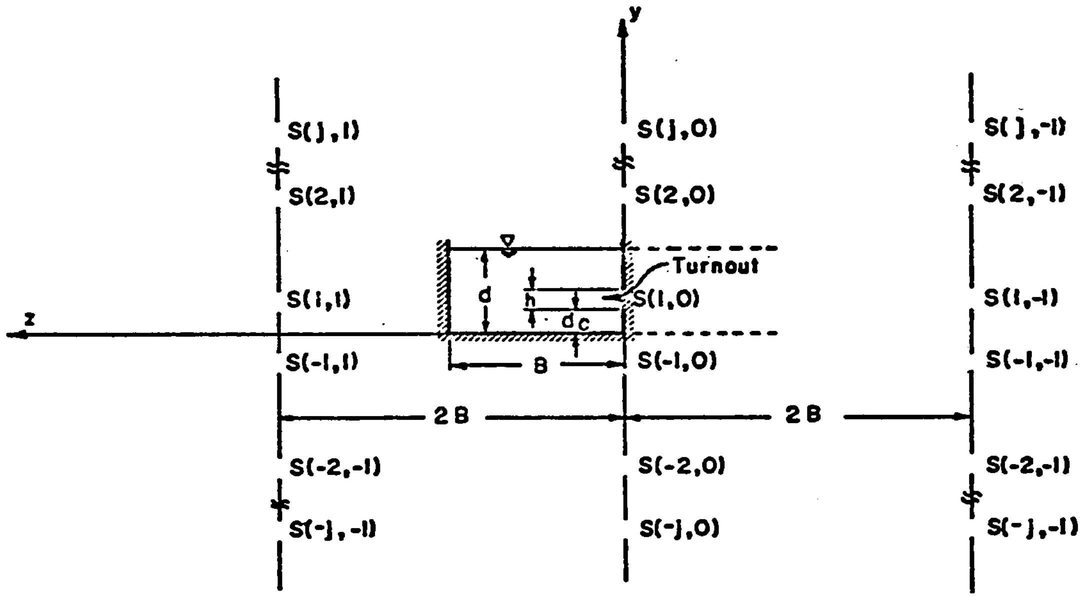

Fig. 8 Arrangement of Uniformly Distributed Sinks to Satisfy Boundary Conditions for Turnout Flow

given by x_f, y_f, z_f where

$$y_f = y_i + \int_0^{t_f} v_p(x,y,z) \cdot dt \tag{11}$$

$$z_f = z_i + \int_0^{t_f} w_p(x,y,z) \cdot dt \tag{12}$$

$$t_f = \int_{x_i}^{x_f} \frac{dx}{u_p(x,y,z)} \tag{13}$$

Equations (11) through (13) are numerically solved. For some of the points (x_u, y_i, z_i), the path lines will enter S(1,0) representing the turnout. The region in Y-Z plane at $x = x_u$, from which the path lines enter S(1,0) is then considered to be feeding water to the turnout. If the curvature of the path lines is negligible, it can be further assumed that the sediment content of this parcel of flow does not alter between the uniform flow in the channel and the entrance to the turnout. For this condition the sediment conduction of the turnout can be determined by the integration of the equilibrium sediment concentration profiles in the channel (2).