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CALCULATION PROCEDURE FOR SAND TRANSPORT BY WIND ON NATURAL BEACHES

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FOREWORD

Sand transport by wind is a major factor involving stability of the beach and backshore in some areas. Experimental work on this subject which validated findings of previous investigators with respect to the rate of such transport by wind, was presented in earlier U. S. Army Corps of Engineers publications (Technical Memorandum No. 119 of the former Beach Erosion Board - "Sand Movement by Wind Action: or Characteristics of Sand Traps", and Technical Memorandum No. 1 of the Coastal Engineering Research Center - "Sand Movement by Wind"). The brief report herein summarizes available methods for calculating the actual rate of sand transport by wind and presents specific procedures and calculations for annual transport from the beach inland by wind at a natural beach locality in California.

This report was prepared at the Wave Research Laboratory of the Institute of Engineering Research of the University of California at Berkeley in pursuance of contract DA-49-055-civ-eng-63-4 with the Beach Erosion Board which provides in part for the study of sand movement by wind. The author of this report, Abdel-Latif Kadib, was a graduate student at the time this work was accomplished.

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TABLE OF CONTENTS

CALCULATION PROCEDURE FOR SAND TRANSPORT BY WIND ON NATURAL BEACHES

by

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INTRODUCTION

The estimation of the annual amount of sand transported along the coast is important for planning and constructing coastal structures. One of the motive forces for transporting sand along the coast is the well-known littoral current generated by wave action, and the other is the wind. Sand movement by wind action has been treated by several research workers. In this report, a summary of some of the available methods of calculating rate of sand transport by wind, and calculations for annual sand transport inland by wind from natural beaches are presented.

SAND TRANSPORT BY WIND

Several investigators have developed expressions for the rate of sand movement as a function of certain variables. Some of these expressions are as follows:

Bagnold Formula:(1)* The rate of sand movement per unit width and unit time, q, is given by:

$$q = c \sqrt{\frac{d}{D}} \frac{\gamma}{g} U_*^3 \qquad (1)$$

where D is the grain diameter of standard 0.25 mm sand, d is the grain diameter of sand in question, γ is the specific weight of air, U_* is the shear velocity, and c has the following values:

* References on page 11.

1.5 for a nearly uniform sand
1.8 for a naturally graded sand
2.8 for sand with a very wide range of grain diameter

Kawamura Formula:[5] The rate of sand movement, q, is given by:

$$q = K \frac{\gamma}{g} (U_* - U_{*t}) (U_* + U_{*t})^2 \qquad (2)$$

where γ is the specific weight of air, U_* is the shear velocity, and U_{*t} is the threshold shear velocity, and K is a constant which must be determined by experiment.

O'Brien and Rindlaub Formula:[7] O'Brien and Rindlaub proposed the following formula from data derived by field tests

$$G = 0.036\, U_5^3 \text{ (for } U_5 > 20 \text{ ft/sec)} \qquad (3)$$

where G is the rate of transport in pounds per day per foot width, and U_5 is the wind velocity at 5 feet above the sand surface in ft/sec. However, the use of this formula should be limited to sand having the same grain diameter of that existing in the field tests[6] (0.195 mm).

WIND VELOCITY ABOVE A SAND SURFACE

The shear stress, τ, produced at the sand surface by wind is one of the most important factors in investigating sand movement by wind action. When the shear stress exceeds a certain critical value, the sand particles start to move. As long as there is no sand movement, the wind-velocity distribution can be described adequately by the general equation

$$U = C \text{ Log } \frac{Z}{Z_o} \qquad (4)$$

in which U is the velocity at height Z above the sand surface and Z_o is a reference parameter. The coefficient, C, according to von Karman's development, is equal to $\frac{2.3}{K} U_*$, where K is the Karman constant, U_* is the shear velocity defined as $\sqrt{\frac{\tau}{\rho}}$, and ρ is the density of air. For K equals 0.40, the von Karman equation becomes

$$U = 5.75\ U_* \text{ Log } \frac{Z}{Z_o} \qquad (5)$$

Concerning the roughness factor, Z_o, Zingg[8] proposed the equation

$$Z_o = 0.081 \text{ Log } \frac{d}{0.18} \qquad (6)$$

where Z_o and the sand grain diameter, d, are expressed in mm. Once the wind velocity is great enough to move sand particles, the velocity profiles for different wind speeds seem to meet at a certain point, which he called a "focus." The height of the focus, Z', appears to be associated with the height of the ripples which form on the surface. Studies made by Zingg allow one to predict the focus by means of the formula,

$$Z' = 10d \text{ millimeters} \qquad (7)$$

$$U' = 20d \text{ miles/hour} \qquad (8)$$

where the grain diameter, d, is expressed in millimeters. Thus, using the component of the focus, Z', U', the wind-velocity distribution can be expressed by

$$U = C \text{ Log } \frac{Z}{Z'} + U' \qquad (9)$$

Bagnold assumed a coefficient C of 5.75 U_*, which corresponds to the value of 0.40 for the Karman constant. But the experiments by Zingg yielded the equation

$$U = 6.13\ U_* \text{ Log } \frac{Z}{Z'} + U' \qquad (10)$$

which indicates values of 0.375 for the Karman constant.

APPLICATION TO NATURAL BEACHES

An illustration of the application of the methods of calculating sand transport by wind was made for Salmon Beach near Bodega Head in northern California (Figure 1). Sand samples were taken at the mid-tide level, or reference point, for eight localities along the coast from Salmon Creek to Mussel Point, a distance of more than 2 miles. Figure 2

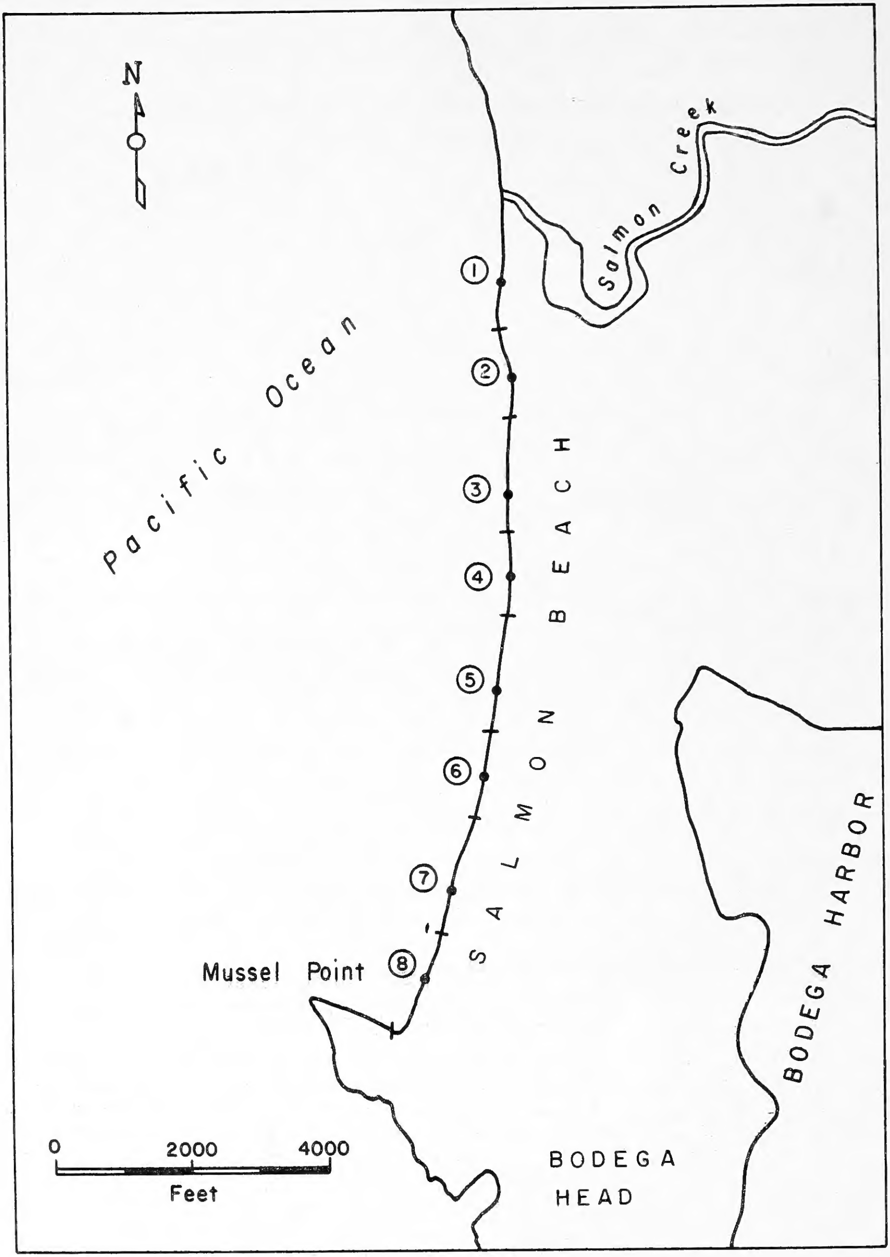

FIG. I NUMBER AND LOCATION OF REACHES AND SAND SAMPLES

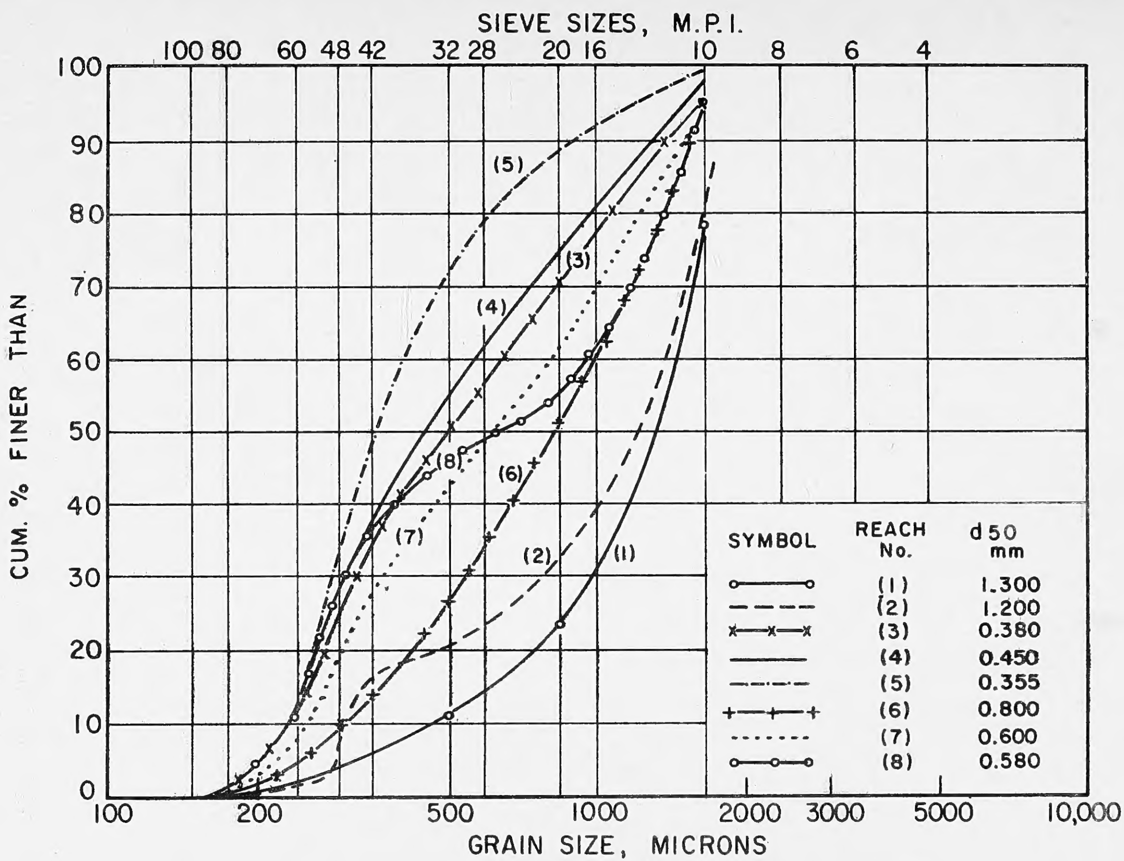

FIG. 2 MECHANICAL ANALYSIS OF BEACH SAMPLES

shows the grain size distribution of sand.* The mean diameter of the sand (d_{50}) was found to vary from 1.3 mm at Salmon Creek to 0.35 mm halfway between Salmon Creek and Mussel Point. According to the grain size variations and the alignment of the coastline in the area considered, the whole distance was divided into eight reaches (Figure 1). Table 1** shows the characteristics of each reach.

Transport Calculations. At this point, one should ask, what method is to be used for calculating the transport? It is clear from previous work[2,6] that the Bagnold formula seems to be superior to any other formula for the following reasons:

1. Bagnold's equation considers the grain-size diameter (Equation 1), and since we have a significant change in d_{50} from reach to reach, the Bagnold formula seems superior.

2. The value of the coefficient C in the Bagnold formula is better defined and more limited in range than the coefficient K in the Kawamura formula.[4]

3. The Kawamura formula (Equation 2) also includes the threshold shear velocity which introduces a further uncertainty in the calculations of transport rate, especially since the factor is influenced by the moisture content of the sand.[2]

4. The use of the O'Brien and Rindlaub formula is not good here, since it has been shown that their equation should be limited to sand having the same grain diameter of that tested in the field,[6] ($d_{50} = 0.195$ mm)

Accordingly, the Bagnold formula will be used in the following calculations for sand transport.

Equation (1) gives the transport in pounds per second per one-foot length. Rewriting Equation (1) in a more general way

$$Q = C \cdot \ell \cdot T \cdot \sqrt{\frac{d}{D}} \frac{\gamma}{g} U_*^3 \qquad (11)$$

*Since the sand size of the reference point is a measure of the sand being moved along the coast as littoral drift, it is also the sand that is moved back into the dune area by wind action.

**Tables at end of text.

where

Q = total transport in pounds per year

C = Bagnold constant

ℓ = length of reach in feet perpendicular to direction of wind considered

d = average grain diameter of sand considered (d_{50} mm)

D = average grain diameter of standard 0.25 mm sand

γ = specific weight of air = (0.076 lbs/ft^3)

U_* = shear velocity in ft/sec

T = duration of wind in seconds per year

g = acceleration due to gravity = 32.2 ft/sec^2

Now substituting the values of γ, g, and choosing $C = 1.8$, since the sand considered has a natural grading, we obtain from Equation (11)

$$Q = 1.8 \cdot \ell \cdot t \cdot 3.6 \cdot 10^3 \sqrt{\frac{d}{D}} \cdot \frac{0.076}{32.2} \cdot U_*^3$$

$$Q = 15.20\ t \cdot \ell \frac{d}{D} U_*^3 \text{ in pounds per year} \qquad (12)$$

where t is in hours per year.

Wind Duration per Year "t". Duration in hours of winds of various speeds from various directions was collected from data obtained from the Pacific Marine Station, Dillon Beach, California. Data were available for the period September 1, 1962 to August 31, 1963 which gave us one year of records. These data are shown in Figure 3. In Table 2 these data are summarized for calculation purposes. Wind speeds below 10 mph were considered calm, since their contribution to transport may be neglected. The uneven values of wind speeds shown in both Figure 3 and Table 2 resulted from the reduction of the wind data from the anemometer chart and the calibration curve of the anemometer. Total number of hours contributing to transport (greater than 10 mph) was 1135 hours; calm hours 3555 and for 4070 hours the anemometer was inoperative.

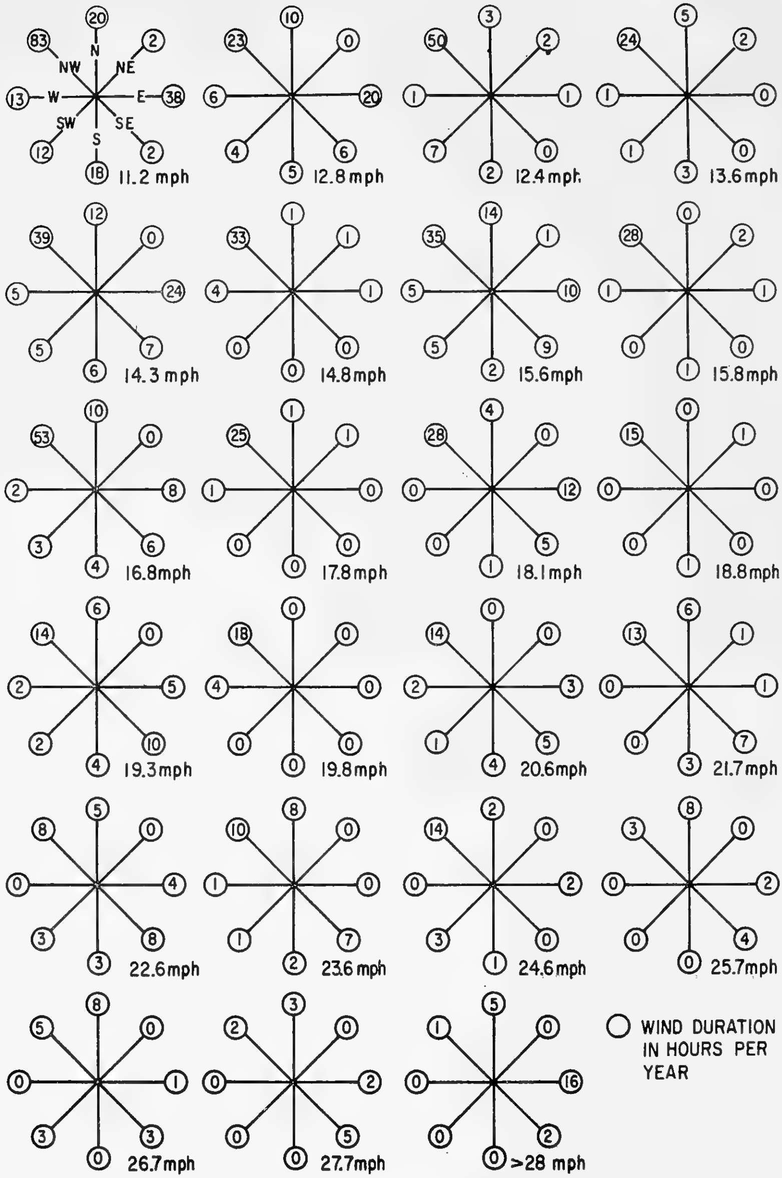

FIG. 3 DURATION OF WIND IN HOURS PER YEAR FOR DIFFERENT WIND VELOCITIES AS OBTAINED FROM PACIFIC MARINE STATION

Length of Reach Contributing to Inland Transport. Considering the eight different possible wind directions, that is, N, NE, E, SE, S, SW, W, and NW, it seems that only four directions cause inland sand transport at Salmon Beach. These directions are N, NW, W, and SW. The perpendicular projections ℓ_2, ℓ_4, ℓ_1, and ℓ_2, respectively, of these directions (Figure 4) were measured and shown in Table 3. These lengths ℓ_1, ℓ_2, ℓ_3, and ℓ_4 represent ℓ in Equation 12 for total transport calculations.

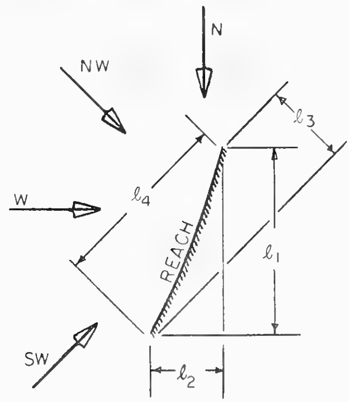

Fig. 4

Shear Velocity U_*. Equation 10 was used to obtain U_* as follows:

$$U = 6.13\ U_* \text{ Log } \frac{Z}{Z'} + U'$$

$$6.13\ U_* \text{ Log } \frac{Z}{Z'} = U - U'$$

$$U_* = \frac{U - U'}{6.13 \text{ Log } \frac{Z}{Z'}} \qquad (13)$$

U' and Z' were calculated using Zingg's formula and are tabulated in Table 4.

Equation 13 was used to determine U_*. All wind-speed measurements were made 18 feet above the sand surface, so this value was used for Z in Equation 13 throughout the calculations.

A sample calculation is

Reach 1

d_{50} = 1.3 mm

From Table 4,

Z' = 0.0427 ft.
U' = 38.00 ft/sec

Consider wind speed 27.7 mph = 40.70 ft/sec

From Equation 13

$$U_* = \frac{\bar{U} - U'}{6.13 \operatorname{Log} \frac{Z}{Z'}}$$

$$= \frac{40.70 - 38.00}{6.13 \operatorname{Log} \frac{18}{.0427}} = 0.168 \text{ ft/sec}$$

The same calculations were made for all reaches, and at different wind speeds. The calculated data are summarized in Table 5.

Total Annual Transport Q. Now having all the data required for calculation of transport Q (Equation 12), the total annual transport was calculated for each reach, for all wind directions contributing to inland transport. Tables 6 through 13 show these calculations.

The total annual inland transport Q was found to be about 10,700 cubic yards per year (Table 14). It should be noted that this quantity perhaps is on the low side since the anemometer was inoperative for many hours during the year. It should also be noted that no reduction was made in rate of transport for sand being in the moist condition as investigated by Belly[2].

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Table 1

Physical Characteristics of Salmon Beach

Reach No	Length along the Coastline (ft)	d_{50} (mm)	$\sqrt{\frac{d_{50}}{D}}$	Remarks
1	2200	1.30	2.29	Naturally graded sand
2	1350	1.20	2.20	"
3	1700	0.380	1.24	"
4	1200	0.450	1.35	"
5	1700	0.355	1.22	"
6	1350	0.800	1.80	"
7	1800	0.600	1.55	"
8	1800	0.580	1.53	"

Table 2

Duration of Wind Per Year for Different Wind Speed (Pacific Marine Station)

Speed ft/sec.	Speed mph	Duration of Wind (Hours per Years)							
		N	NW	W	SW	S	SE	E	NE
14.7	10	4	45	3	5	2		1	1
16.5	11.2	20	83	13	12	18	2	38	2
18.2	12.4	3	50	1	7	2		1	2
18.8	12.8	10	23	6	4	5	6	20	
20.	13.6	5	24	1	1	3			2
21.02	14.3	12	39	5	5	6	7	24	
21.8	14.8	1	33	4				1	1
22.9	15.6	14	35	5	5	2	9	10	1
23.2	15.8		28	1		1		1	2
24.7	16.8	10	53	2	3	4	6	8	
26.2	17.8	1	25	1					1
26.6	18.1	4	28			1	5	12	
27.6	18.8		15			1			1
28.4	19.3	6	14	2	2	4	10	5	
29.1	19.8		18	4					
30.3	20.6		14	2	1	4	5	3	
32.	21.7	6	13			3	7	1	1
33.2	22.6	5	8		3	3	8	4	
34.7	23.6	8	10	1	1	2	7		
36.3	24.6	2	14		3	1		2	
37.8	25.7	8	3				4	2	
39.3	26.7	8	5		3		3	1	
40.7	27.7	3	2				5	2	
> 41.2	>28.0	5	1				2	16	

Total hrs - 1135 hrs. of wind > 10 mph

Calm - 3555 hrs.

No records - 4070 hrs.

Table 3

Perpendicular Projections for Different Wind Directions*

Reach No.	Length ℓ (ft)	Representing grain dia. d_{50} (mm)	ℓ_1 (ft)	ℓ_2 (ft)	ℓ_3 (ft)	ℓ_4 (ft)
1	2200	1.30	1900	200	1400	1450
2	1500	1.20	1400	200	900	900
3	1700	0.38	1600	150	1150	1300
4	1200	0.45	1150	150	850	800
5	1700	0.355	1500	400	1100	1400
6	1350	0.80	1300	300	700	1000
7	1800	0.60	1700	500	900	1500
8	1800	0.58	1400	900	500	1700

* South, SE, E and NE winds do not contribute to inland movement

Table 4

Calculations for the Focal Point Using the Zingg Formula

Reach No.	d_{50} mm	Z' = 10 d mm	Z' (ft)	U' = 20dm (m/h)	U' ft/sec
1	1.30	13.0	0.0427	26.00	38.00
2	1.20	12.0	0.0394	24.0	35.00
3	0.38	3.8	0.0125	7.6	11.30
4	0.45	4.5	0.0147	9.0	13.20
5	0.355	3.55	0.0116	7.10	10.40
6	0.80	8.0	0.0262	16.00	23.50
7	0.60	6.0	0.0197	12.00	17.60
8	0.58	5.80	0.019	11.60	17.00

Table 5

Calculation of U_* for Different Reaches and Wind Speeds

$$U_* = \frac{U_{18} - U'}{6.13 \text{ Log } Z/Z'} \quad \text{ft/sec}$$

U_{18} ft/sec	Reach No. 1	Reach No. 2	Reach No. 3	Reach No. 4	Reach No. 5	Reach No. 6	Reach No. 7	Reach No. 8
14.70	-	-	0.175	0.079	0.22	-	-	-
16.50	-	-	0.268	0.175	0.310	-	-	-
18.20	-	-	0.356	0.264	0.40	-	0.033	0.065
18.8	-	-	0.385	0.286	0.428	-	0.066	0.098
20.0	-	-	0.45	0.358	0.49	-	0.130	0.164
21.02	-	-	0.50	0.410	0.55	-	0.19	0.22
21.8	-	-	0.54	0.450	0.58	-	0.23	0.26
22.9	-	-	0.61	0.510	0.635	-	0.29	0.32
23.2	-	-	0.615	0.53	0.64	-	0.31	0.34
24.7	-	-	0.690	0.605	0.73	0.069	0.39	0.42
26.2	-	-	0.780	0.695	0.815	0.167	0.48	0.51
26.6	-	-	0.795	0.710	0.825	0.180	0.49	0.525
27.6	-	-	0.840	0.760	0.88	0.235	0.55	0.58
28.4	-	-	0.88	0.800	0.92	0.29	0.59	0.621
29.1	-	-	0.918	0.84	0.954	0.328	0.63	0.66
30.3	-	-	0.98	0.90	0.97	0.40	0.694	0.73
32.0	-	-	1.07	0.99	1.06	0.494	0.73	0.81
33.2	-	-	1.13	1.053	1.12	0.56	0.80	0.882
34.7	-	-	1.15	1.13	1.20	0.65	0.88	0.964
36.3	-	0.074	1.24	1.22	1.28	0.74	0.97	1.05
37.8	-	0.172	1.32	1.29	1.35	0.83	1.05	1.19
39.3	.082	0.265	1.39	1.37	1.43	1.00	1.13	1.27
40.7	0.168	0.31	1.464	1.44	1.50	1.10	1.207	1.35
>41.2								

Table 6

Total Transport Per Year - Reach No. 1

Reach No. 1 $\sqrt{\frac{d}{D}} = 2.29$

U ft/sec	U_* ft/sec	U_*^3	N: t (hrs)	N: $U_*^3 t \ell$	N: ℓ_2 (ft)	NW: t (hrs)	NW: $U_*^3 t \ell$	NW: ℓ_4 (ft)	W: t (hrs)	W: $U_*^3 t \ell$	W: ℓ_1 (ft)	SW: t (hrs)	SW: $U_*^3 t \ell$	SW: ℓ_3 (ft)
39.30	0.082	0.55×10^{-3}	8	0.88	200.00	5	4.00	1450.00	0	0	1900.00	3	2.31	1400.00
40.70	0.168	0.0047	3	2.82	200.00	2	13.65	1450.00	0	0	1900.00	0	0	1400.00
>41.20	$\simeq$0.20	0.008	5	8.00	200.00	1	11.60	1450.00	0	0	1900.00	0	0	1400.00

$\Sigma U_*^3 \ell t = 43.26$

$Q_1 = 2.29 \times 15.2 \times 43.26 = 1600$ lb/year

Table 7

Total Transport Per Year - Reach 2

Reacn No. 2 $\sqrt{\frac{d}{D}} = 2.20$

			N			NW			W			SW		
U ft/sec	U_* ft/sec	U_*^3	t (hrs)	ℓ_2 (ft)	$\ell t U_*^3$	t (hrs)	ℓ_4 (ft)	$\ell t U_*^3$	t (hrs)	ℓ_1 (ft)	$\ell t U_*^3$	t (hrs)	ℓ_3 (ft)	$\ell t U_*^3$
36.3	0.074	0.405×10^{-3}	2	200.00	0.162	14	900.00	5.100	0	-	0	3	900.00	1.09
37.8	0.172	0.005	8	200.00	8.000	3	900.00	13.500	0	-	0	0	900.00	0
39.30	0.265	0.0185	8	200.00	29.600	5	900.00	83.200	0	-	0	3	900.00	50.00
40.70	0.310	0.0295	3	200.00	17.800	2	900.00	53.200	0	-	0	0	900.00	0
>41.2	0.40	0.064	5	200.00	64.00	1	900.00	57.00	0	-	0	0	900.00	0

$\Sigma U_*^3 \ell t = 382.652$

$Q_2 = 2.20 \times 15.20 \times 382.652$

$= 12,820$ lb/year

Table 8
Total Transport Per Year, Reach 3

Reach No. 3 $\sqrt{\frac{d}{D}} = 1.24$

U ft/sec	U* ft/sec	U_*^3	N: t hrs	N: ℓ ft2	N: U*3t	NW: t hrs	NW: ℓ_4 ft	NW: U*3t	W: t hrs	W: ℓ_1 ft	W: U*3	SW: t hrs	SW: ℓ_3 ft	SW: U*3 t
14.7	0.175	0.0054	4	150	0.022	45	1300	0.244	3	1600	0.016	5	1150	0.027
16.5	0.268	0.0190	20	150	0.380	83	1300	1.450	13	1600	0.247	12	1150	0.208
18.2	0.356	0.045	3		0.135	50	1300	2.25	1	1600	0.045	7	1150	0.315
18.8	0.385	0.057	10	150	0.570	23	1300	1.32	6	1600	0.342	4	1150	0.228
20.	0.450	0.090	5	150	0.450	24	1300	2.16	1	1600	0.090	1	1150	0.450
21.02	0.50	0.125	12	150	1.500	39	1300	4.87	5	1600	0.625	5	1150	0.625
21.8	0.54	0.154	1	150	0.154	33	1300	5.10	4	1600	0.616	0	1150	0.00
22.9	0.61	0.221	14	150	3.184	35	1300	7.72	5	1600	1.105	5	1150	1.105
23.2	0.615	0.230	0	150	0.000	28	1300	6.45	1	1600	0.230	0	1150	0.00
24.7	0.690	0.322	10	150	3.220	53	1300	17.20	2	1600	0.644	3	1150	0.966
26.2	0.780	0.470	1	150	0.470	25	1300	11.80	1	1600	0.470	0	1150	0.00
26.6	0.795	0.500	4	150	2.000	28	1300	14.00	0	1600	0.00	0	1150	0.00
27.6	0.84	0.582	0	150	0.00	15	1300	8.20	0	1600	0.00	0	1150	0.00
28.4	0.88	0.670	6	150	4.020	14	1300	9.36	2	1600	1.340	2	1150	1.340
29.1	0.92	0.770	0	150	0.00	18	1300	13.85	4	1600	3.080	0	1150	0.00
30.3	0.98	0.940	0	150	0.000	14	1300	13.20	2	1600	1.880	1	1150	0.94
32.0	1.07	1.30	6	150	7.800	13	1300	16.90	0	1600	0.00	0	1150	0.00
33.2	1.13	1.42	5	150	9.100	8	1300	11.36	0	1600	0.00	3	1150	4.26
34.7	1.15	1.52	8	150	12.160	10	1300	15.20	1	1600	1.520	1	1150	1.52
36.3	1.24	1.88	2	150	3.760	14	1300	26.40	0	1600	0.00	3	1150	5.64
37.8	1.32	2.25	8	150	18.000	3	1300	6.75	0	1600	0.00	0	1150	0.00
39.3	1.39	2.65	8	150	21.200	5	1300	13.25	0	1600	0.00	3	1150	7.95
40.7	1.464	3.10	3	150	9.300	2	1300	6.20	0	1600	0.00	0	1150	0.00
>41.2	1.80	5.83	5	150	29.150	1	1300	5.83	0	1600	0.00	0	1150	0.00

$\Sigma_N U_*^3 \ell t = 129.995 \times 150$ $\Sigma_{NW} U_* \ell t = 221.174 \times 1300$ $\Sigma_W \ell U_*^3 t = 12.25 \times 1300$ $\Sigma_{SW} \ell u_*^3 t = 1150 \times 25.574$

$\Sigma U_*^3 \ell t = 19{,}500 + 287{,}000 + 16{,}100 + 29{,}600 = 352{,}200$

$Q_3 = 1.24 \times 15.2 \times 352{,}200 = 6{,}650{,}000$ lb/year

Table 9

Total Transport Per Year, Reach 4

Reach No. 4 $\sqrt{\frac{d}{D}} = 1.35$

U	U*	U^{*3}	N			NW			W			SW		
ft/sec	ft/sec		t hrs	ℓ_2 ft	$U^{*3}t$	t hrs	ℓ_4 ft	$U^{*3}t$	t hrs	ℓ_1 ft	$U^{*3}t$	t hrs	ℓ_3 ft	$U^{*3}t$
14.7	0.079	.0005	4	150.00	.002	45	800.00	.0225	3	1150.00	..0015	5	850	.0025
16.5	0.175	.0053	20	150.00	0.106	83	800.00	0.440	13	1150.00	.069	12	850	.0635
18.20	0.264	0.0185	3	150.00	0.555	50	800.00	.925	1	1150.00	.019	7	850	.1295
18.80	0.286	0.0234	10	150.00	0.234	23	800.00	0.57	6	1150.00	0.140	4	850	0.0935
20.00	0.358	0.046	5	150.00	0.230	24	800.00	1.10	1	1150.00	.046	1	850	.046
21.02	0.410	0.0685	12	150.00	0.820	39	800.00	2.66	5	1150.00	0.342	5	850	0.342
21.80	0.45	0.090	1	150.00	0.090	33	800.00	2.96	4	1150.00	0.360	0	850	0.000
22.90	0.51	0.132	14	150.00	1.850	35	800.00	4.64	5	1150.00	0.650	5	850	0.650
23.20	0.53	0.148	0	150.00	0.000	28	800.00	4.15	1	1150.00	0.148	0	850	0.000
24.70	0.605	0.220	10	150.00	2.200	53	800.00	11.65	2	1150.00	0.440	3	850	0.660
26.20	0.695	0.335	1	150.00	0.335	25	800.00	8.36	1	1150.00	0.335	0	850	0.000
26.60	0.710	0.358	4	150.00	1.432	28	800.00	10.024	0	1150.00	0.000	0	850	0.000
27.60	0.76	0.440	0	150.00	0.000	15	800.00	6.600	0	1150.00	0.000	0	850	0.000
28.40	0.80	0.510	6	150.00	3.060	14	800.00	7.140	2	1150.00	1.020	2	850	1.020
29.10	0.84	0.590	0	150.00	0.000	18	800.00	10.60	4	1150.00	2.360	0	850	0.000
30.30	0.90	0.712	0	150.00	0.000	14	800.00	10.000	2	1150.00	1.424	1	850	0.712
32.00	0.99	0.980	6	150.00	5.880	13	800.00	12.700	0	1150.00	0.000	0	850	0.00
33.20	1.053	1.160	5	150.00	5.80	8	800.00	9.28	0	1150.00	0.000	3	850	3.48
34.70	1.130	1.45	8	150.00	11.60	10	800.00	14.50	1	1150.00	0.145	1	850	0.145
36.30	1.22	1.82	2	150.00	3.64	14	800.00	25.50	0	1150.00	0.000	3	850	5.46
37.80	1.29	2.15	8	150.00	17.20	3	800.00	6.45	0	1150.00	0.000	0	850	0.00
39.30	1.37	2.55	8	150.00	20.40	5	800.00	12.75	0	1150.00	0.000	3	850	7.65
40.70	1.44	2.96	3	150.00	8.88	2	800.00	5.92	0	1150.00	0.000	0	850	0.000
>41.2	1.80	5.80	5	150.00	29.00	1	800.00	5.80	0	1150.00		0		0.000
					112.815			174.742			7.500			20.456

$\Sigma U^{*3}\ell t$ = 16,930 + 139,793 + 8,625 + 17,368

= 182,712

Q_4 = 1.35 x 15 · 2 x 182,716 = 3,758,000 lb/year

Table 10

Total Transport Per Year, Reach 5

Reach No. 5 $\sqrt{\frac{d}{D}} = 1.22$

U ft/sec	U* ft/sec	U_*^3	N t hrs	N $U_*^3 t$	N ℓ_2 ft	NW t hrs	NW $U_*^3 t$	NW ℓ_4 ft	W t hrs	W $U_*^3 t$	W ℓ_1 ft	SW t(hrs)	SW U_*^3	SW ℓ_3 ft
14.7	0.220	0.0106	4	0.0424	400.00	48	0.5088	1400.00	3	0.0318	1500	5	0.0530	1100
16.5	0.310	0.0295	20	0.59	400.00	83	2.46	1400.00	13	0.384	1500	12	0.354	1100
18.2	0.400	0.0640	3	0.192	400.00	50	3.20	1400.00	1	0.064	1500	7	0.448	1100
18.8	0.428	0.0780	10	0.780	400.00	23	1.79	1400.00	6	0.467	1500	4	0.312	1100
20.00	0.490	0.1170	5	0.585	400.00	24	2.81	1400.00	1	0.117	1500	1	0.117	1100
21.02	0.550	0.165	12	1.740	400.00	39	6.44	1400.00	5	0.825	1500	5	0.825	1100
21.80	0.580	0.194	1	0.194	400.00	33	6.40	1400.00	4	0.776	1500	0	0.00	1100
22.90	0.6350	0.260	14	3.64	400.00	35	9.10	1400.00	5	1.300	1500	5	1.300	1100
23.20	0.640	0.262	0	0.00	400.00	28	7.35	1400.00	1	0.262	1500	0	0.00	1100
24.70	0.730	0.388	10	3.88	400.00	53	20.600	1400.00	2	0.776	1500	3	1.164	1100
26.2	0.815	0.540	1	0.540	400.00	25	13.50	1400.00	1	0.540	1500	0	0.00	1100
26.6	0.825	0.560	4	2.24	400.00	28	15.70	1400.00	0	0.00	1500	0	0.00	1100
27.6	0.880	0.680	0	0.00	400.00	15	10.2	1400.00	0	0.00	1500	0	0.00	1100
28.4	0.92	0.780	6	4.68	400.00	14	10.9	1400.00	2	1.56	1500	2	1.56	1100
29.10	0.954	0.860	0	0.00	400.00	18	15.5	1400.00	4	3.44	1500	0	0.00	1100
30.30	0.970	0.910	0	0.00	400.00	14	12.72	1400.00	2	1.82	1500	1	0.910	1100
32.00	1.060	1.180	6	7.08	400.00	13	15.35	1400.00	0	0.000	1500	0	0.00	1100
33.20	1.120	1.40	5	7.00	400.00	8	11.2	1400.00	3	0.000	1500	3	4.2	1100
34.70	1.200	1.72	8	12.76	400.00	10	17.20	1400.00	1	1.72	1500	1	1.72	1100
36.30	1.280	2.10	2	4.20	400.00	14	29.4	1400.00	0	0.00	1500	3	6.30	1100
37.80	1.350	2.45	8	19.60	400.00	3	7.35	1400.00	0	0.00	1500	0	0.00	1100
39.30	1.430	2.90	8	23.20	400.00	5	14.5	1400.00	0	0.00	1500	3	11.7	1100
40.70	1.500	3.38	3	10.14	400.00	2	6.76	1400.00	0	0.00	1500	0	0.00	1100
>41.20	1.800	5.80	5	29.0	400.00	1	5.80	1400.00	0	0.00	1500	0	0.00	1100
				132.083			246.739			14.083			30.963	

$\Sigma \ell t U_*^3$ = 52,835 + 347,000 + 21 125 + 34,100

= 455,060

Q_5 = 1.22 x 15 . 2 x 455,060 = 8,450,000 lb/year

Table 11

Total Transport Per Year, Reach 6

Reach No. 6 $\sqrt{\frac{d}{D}} = 1.80$

U ft/sec	U^* ft/sec	U^{*3}	N t (hrs)	N tU_*^3	N ℓ_2 ft	NW t (hrs)	NW tU_*^3	NW ℓ_4 ft	W t (hrs)	W tU_*^3	W ℓ_1 ft	SW t hrs	SW tU_*^3	SW ℓ_3 (ft)
24.70	0.069	0.00033	10	0.003	300.00	53	0.018	1000	2	0.0007	1300	3	0.001	700
26.20	0.167	.00465	1	.005	300.00	25	0.116	1000	1	0.005	1300	0	0.00	700
26.60	0.180	.0058	4	.0232	300.00	28	0.162	1000	0	0.000	1300	0	0.00	700
27.60	0.235	0.0128	0	0.000	300.00	15	0.195	1000	0	0.000	1300	0	0.00	700
28.40	0.290	.0242	6	.1452	300.00	14	0.340	1000	2	0.048	1300	2	0.00	700
29.10	0.330	.0353	0	0.000	300.00	18	0.645	1000	4	0.1432	1300	0	0.000	700
30.30	0.40	.0640	0	0.00	300.00	14	0.900	1000	2	0.128	1300	1	0.064	700
32.00	0.50	0.125	6	0.750	300.00	13	1.625	1000	0	0.00	1300	0	0.000	700
33.20	0.56	0.176	5	.950	300.00	8	1.408	1000	0	0.00	1300	3	0.528	700
34.70	0.65	0.275	8	2.200	300.00	10	2.75	1000	1	0.275	1300	1	0.275	700
36.30	0.74	0.400	2	.800	300.00	14	5.60	1000	0	0.00	1300	3	1.200	700
37.80	0.83	0.5700	8	4.56	300.00	3	1.71	1000	0	0.000	1300	0	0.000	700
39.30	1.00	1.000	8	8.00	300.00	5	5.000	1000	0	0.000	1300	3	3.00	700
40.70	1.10	1.331	3	3.993	300.00	2	2.662	1000	0	0.000	1300	0	0.00	700
>41.20	1.20	1.728	5	8.640	300.00	1	1.728	1000	0	0.000	1300	0	0.00	700
				30.069			24.859			0.599			5.116	

$\Sigma U_*^3 \ell t$ = 9,021 + 24,859 + 776.00 + 3,581

= 38,237

Q_6 = 1.80 x 15·2 x 38,237 = 1,050,000 lb/year

Table 12

Total Transport Per Year , Reach 7

Reach No. 7 $\sqrt{\frac{d}{D}} = 1.55$

U ft/sec	U_* ft/sec	U_*^3	N t(hrs)	N tU_*^3	ℓ_2 (ft)	NW t(hrs)	NW tU_*^3	ℓ_4 (ft)	W t(hrs)	W tU_*^3	ℓ_1 (ft)	SW t(hrs)	SW tU_*^3	ℓ_3 ft
18.2	0.033	0.000036	3	0.00012	500.00	50	0.002	1500.00	1	0.000	1700.00	7	0	900.00
18.8	0.066	.000285	10	.0030	500.00	23	0.007	1500.00	6	0.002	1700.00	4	0.001	900.00
20.00	0.130	.0022	5	0.011	500.00	24	0.0528	1500.00	1	.002	1700.00	1	.002	900.00
21.02	0.190	.0068	12	0.082	500.00	39	0.272	1500.00	5	.034	1700.00	5	.034	900.00
21.80	0.230	.0121	1	0.012	500.00	33	0.399	1500.00	4	0.048	1700.00	0	.0	900.00
22.90	0.290	.0242	14	0.340	500.00	35	0.792	1500.00	5	0.121	1700.00	5	0.121	900.00
23.20	0.310	.0295	0	0.000	500.00	28	0.840	1500.00	1	0.030	1700.00	0	0	900.00
24.70	0.390	.0590	10	0.590	500.00	53	2.927	1500.00	2	0.118	1700.00	3	0.177	900.00
26.20	0.480	0.1100	1	0.110	500.00	25	2.750	1500.00	1	0.110	1700.00	0	0	900.00
26.60	0.49	0.117	4	0.468	500.00	28	3.276	1500.00	0	0.00	1700.00	0	0	900.00
27.6	0.55	0.166	0	0.000	500.00	15	2.790	1500.00	0	0.00	1700.00	0	0	900.00
28.40	0.59	0.205	6	1.230	500.00	14	2.870	1500.00	2	0.410	1700.00	2	0.210	900.00
29.10	0.63	0.249	0	0.00	500.00	18	4.500	1500.00	4	0.996	1700.00	0	0	900.00
30.30	0.70	0.343	0	0.00	500.00	14	4.760	1500.00	2	0.686	1700.00	1	0.343	900.00
32.00	0.73	0.386	6	2.376	500.00	13	5.070	1500.00	0	0.00	1700.00	0	0	900.00
33.20	0.80	0.512	5	2.560	500.00	8	4.096	1500.00	0	0.00	1700.00	3	1.536	900.00
34.70	0.88	0.680	8	5.440	500.00	10	6.800	1500.00	1	0.680	1700.00	1	0.680	900.00
36.3	0.97	0.955	2	1.910	500.00	14	13.650	1500.00	0	0	1700.00	3	2.865	900.00
37.8	1.05	1.150	8	9.200	500.00	3	3.450	1500.00	0	0	1700.00	0	0	900.00
39.3	1.13	1.45	8	11.60	500.00	5	7.250	1500.00	0	0	1700.00	3	4.350	900.00
40.70	1.21	1.76	3	5.280	500.00	2	3.520	1500.00	0	0	1700.00	0	0	900.00
>41.2	1.40	2.75	5	13.750	500.00	1	2.750	1500.00	0	0	1700.00	0	0	900.00
				54.902			72.924			3.237			10.349	

$\Sigma U_*^3 \ell t$ = 27,500 + 109,500 + 5,508 + 9,305

= 151,813

Q_7 = 1.55 x 15.2 x 151,813 = 3,600,000 lb/year

Table 13
Total Transport Per Year, Reach 8

Reach No. 8 $\sqrt{\frac{d}{D}} = 1.530$

U ft/sec	U_* ft/sec	U_*^3	N t hrs	N $U_*^3 t$	ℓ_2 ft	NW t hrs	NW $U_*^3 t$	ℓ_4 ft	W t hrs	W $U_*^3 t$	ℓ_1 ft	SW t hrs	SW $U_*^3 t$	ℓ_3 ft
18.20	0.0650	0.000275	3	0.001	900.00	50	0.015	1700.00	1	0.0	1400.00	7	0.002	500.00
18.80	0.0980	.000960	10	.010	900.00	23	.023	1700.00	6	.006	1400.00	4	0.004	500.00
20.00	0.164	.0044	5	.022	900.00	24	.120	1700.00	1	.004	1400.00	1	.004	500.00
21.00	0.220	0.011	12	.121	900.00	39	0.440	1700.00	5	.055	1400.00	5	.055	500.00
21.80	0.260	0.018	1	.018	900.00	33	0.594	1700.00	4	.072	1400.00	0	0	500.00
22.90	0.320	0.0325	14	.435	900.00	35	1.165	1700.00	5	0.165	1400.00	5	0.165	500.00
23.20	0.340	0.039	0	0	900.00	28	1.092	1700.00	1	.039	1400.00	0	0	500.00
24.70	0.420	0.072	10	0.720	900.00	53	3.816	1700.00	?	0.144	1400.00	3	0.216	500.00
26.20	0.510	0.143	1	0.143	900.00	25	3.560	1700.00	1	0.143	1400.00	0	0	500.00
26.60	0.525	0.145	4	.580	900.00	28	4.060	1700.00	0	0	1400.00	0	0	500.00
27.60	0.580	0.194	0	0	900.00	15	2.910	1700.00	0	0	1400.00	0	0	500.00
28.40	0.621	0.240	6	1.440	900.00	14	3.340	1700.00	2	.480	1400.00	2	0.480	500.00
29.10	0.660	0.286	0	0	900.00	18	5.148	1700.00	4	1.144	1400.00	0	0	500.00
30.30	0.730	0.386	0	0	900.00	14	5.152	1700.00	2	0.772	1400.00	1	0.386	500.00
32.00	0.810	0.530	6	3.180	900.00	13	6.890	1700.00	0	0	1400.00	0	0	500.00
33.20	0.882	0.682	5	3.410	900.00	8	5.456	1700.00	0	0	1400.00	3	2.046	500.00
34.70	0.964	0.900	8	7.200	900.00	10	9.000	1700.00	1	.900	1400.00	1	.900	500.00
36.30	1.050	1.150	2	2.300	900.00	14	16.000	1700.00	0	0	1400.00	3	3.450	500.00
37.80	1.190	1.725	8	13.800	900.00	3	5.175	1700.00	0	0	1400.00	0	0	500.00
39.30	1.270	2.100	8	16.80	900.00	5	10.500	1700.00	0	0	1400.00	3	6.300	500.00
40.7	1.35	2.45	3	7.350	900.00	2	4.900	1700.00	0	0	1400.00	0	0	500.00
>41.2	1.80	5.800	5	29.00	900.00	1	5.800	1700.00	0	0	1400.00	0	0	500.00
				86.530			85.156			3.924			14.008	

$\Sigma U_*^3 \ell t$ = 77,877 + 145,000 + 5,500 + 7,000

= 230,377

Q_8 = 1.53 x 15.2 x 230,377 = 5,400,000 lb/year

Table 14

Total Transport per Year

Reach	Q (lb)
1	1,600
2	12,820
3	6,650,000
4	3,758,000
5	8,450,000
6	1,050,000
7	3,600,000
8	5,400,000
	28,922,420 lbs.
	≃ 29,000,000 lbs. per year

$$= \frac{29,000,000}{100 \times 27} = 10,690 \text{ cubic yards/year}$$

$$\simeq 10,700 \text{ cubic yards/year}$$

U.S. ARMY COASTAL ENGRG. RES. CENTER, CE., WASH., D.C.

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