RATING CURVES OF LIBERIAN RIVERS
PART IV : RATING CURVES SET

BY
Witold G. Strupczewski
AND
David Z. Sua

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"DEVELOPING WATER RESOURCES"

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1. INTRODUCTION

The purpose of the report is to make a comprehensive study concerning discharge - stage relationships for all hydrological stations in Liberia, and to produce the appropriate set of rating curves. It is needless to say that proper estimation of rating curves is a necessary condition for evaluation of surface water resources in the country. This report is based on three previous ones:

1. Rating Curves of Liberian Rivers, Part I: Methodological Background - Collection of Information and Processing, LHS, June, 1983
2. Rating Curves of Liberian Rivers, Part II: Discharge Measurement data from Inception till June, 1983, LHS, July, 1983
3. Rating Curves of Liberian Rivers, Part III: Hydraulic Estimation, LHS, December, 1983

and as well as on the data recently retrieved from the LHS Archive.

The hydraulic Approach was used where there was paucity of discharge measurement data, while the statistical approach was applied when the number and quality of discharge measurements made it possible. For rating curves derived statistically, the graphical and mathematical representations are given. Calculation of daily discharge from Gauge Height Reading can be easily done by means of "QH" Program.

Rating Curves derived by the hydraulic method are given in the form of Skeleton Rating Tables only.

Below, the listing of "QH" Program is given, accompanied by User Instruction.

```
01 ◇ LBL   "QH"
02 ◇ LBL   Ø1
03   "H  =  ?"
04   PROMPT
```

```
05   RCL   ØØ
06    +
07   RCL   Ø1
08   Y ↑ X
09   RCL   Ø2
1Ø    *
11   "Q = "
12   ARCL X
13   AVIEW
14   R / S
15   GTO   Ø1
16   END
```

User Instruction

(B)	STO ØØ	STORE THE RATING CURVES' PARAMETERS
(n)	STO Ø1	
(A)	STO Ø2	

units:

H in cm, Q in m^3/s

STEP	INSTRUCTIONS	INPUT	FUNCTION	DISPLAY
1	Initialize the Program		XEQ "QH"	H = ?
2	Key in	H	R/S	Q = (Q)
3			R/S	H = ?

2. RATING CURVES

01 00 KN KONGO ON MANO RIVER

PERIOD OF OPERATION: 1958-till now

There are 173 published flow measurement points (Q,H) as per (Ref. 2); these measurements were jointly conducted by the MRU and the LHS. The data spans the period from March, 1976 to July, 1982. Because of the size of the data and considering the limited plotting space, it was necessary to adopt another methodology in isolating points for derivation of the rating equation.

The data were first scrutinized for coherence. At this stage all points proving to be apparently wrong were eliminated from computations. It was found that points 106 to 110 (Ref. 2) were incoherent with the 44 others obtained within that year (1977); they were therefore considered to be wrong. Measurement numbers (Ref. 2), 74, 127, 128, 132, 149 and 150 were similarly treated. It was further observed after the above treatment, that all other points, except those of 1981, were scattered about one curve. Scrutiny of the beta parameter suggests that there may have been a temporary datum change, or that the measurement section was changed during 1981. However, there are no records on this. This suggested giving a special treatment to the 1981 data set. All five (5) points of 1981 were therefore used in deriving a rating equation (Q2) which is appropriate only for that period; while the remaining 157 flow measurement points were grouped in 10 - centimeter gauge height intervals as appears in Table 2.1.

Intervals which are unlisted should be interpreted as having no recorded data as per Ref. 2. The arithmetic mean value of stage and discharge were then obtained for each listed interval resulting in a new series of rating points, ($\bar{Q}_i, \bar{H}_i$; i = 1,2,...,29). It is these points which were used in the statistical derivation of rating equation Q1, by means of the "RAT CUR" computer programme. Accordingly:

Rating Equation I : $Q1 = 1.2146(10^{-3})\ (H + 13.9204)^{2.3380}$

Coefficient of Correlation : $R = 0.9942$

Range of Stage : $29cm \leq H \leq 389cm$

and :

Rating Equation II : $Q2 = 2.3412(H - 43.5159)^{0.8850}$

Coefficient of Correlation : $R = 0.9973$

Range of Stage : $49cm \leq H \leq 269cm$

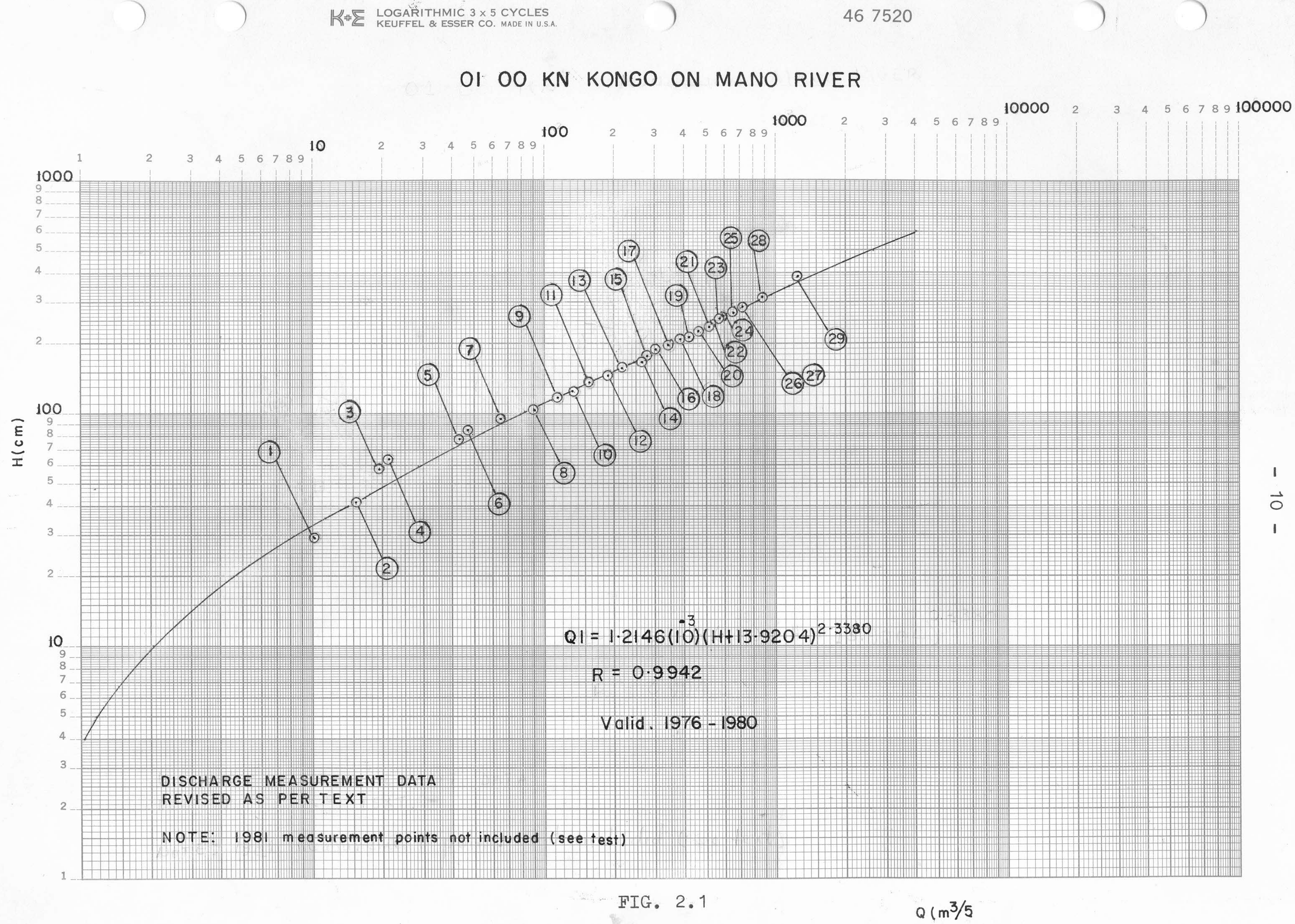
NOTE : Equation II was derived from 1981 data only, as explained in the text.

TABLE 2.1 FLOW MEASUREMENT DATA GROUPED IN 10-CENTIMETER GAUGE HEIGHT INTERVALS PERIOD: 1976-1980

01 00 KN KONGO ON MANO RIVER

* NO	MEAN GAUGE HEIGHT (cm)	MEAN FLOW (m^3/s)	STAGE INTERVAL FROM (cm)	TO (cm)	POINTS IN INTERVAL
1	29	10.1	20	29	1
2	41	15.5	40	49	3
3	57	19.4	50	59	5
4	64	21.1	60	69	8
5	78	43.2	70	79	4
6	84	46.9	80	89	11
7	96	65.7	90	99	4
8	105	91.3	100	109	5
9	115	115.	110	119	9
10	124	134.	120	129	9
11	134	160.	130	139	13
12	145	190.	140	149	11
13	154	220.	150	159	7
14	168	267.	160	169	3
15	175	286.	170	179	5
16	187	306.	180	189	4
17	195	350.	190	199	8
18	204	385	200	209	5
19	215	426	210	219	7
20	222	479	220	229	5
21	233	519	230	239	1
22	246	539	240	249	8
23	253	576	250	259	7
24	264	591	260	269	3
25	275	646	270	279	2
26	288	703	280	289	2
27	292	716	290	299	4
28	317	877	310	319	2
29	389	1211	380	389	1

* Same as those on rating points.



K+E LOGARITHMIC 3 x 5 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 7520
OI OO KN KONGO ON MANO RIVER
H(cm)
Q(m3/5
QI = 1·2146(10)-3(H+13·9204)2·3380
R = 0·9942
Valid. 1976 - 1980
DISCHARGE MEASUREMENT DATA
REVISED AS PER TEXT
NOTE: 1981 measurement points not included (see test)

FIG. 2.1

OI OO KN KONGO ON MANO RIVER (Cont'd)

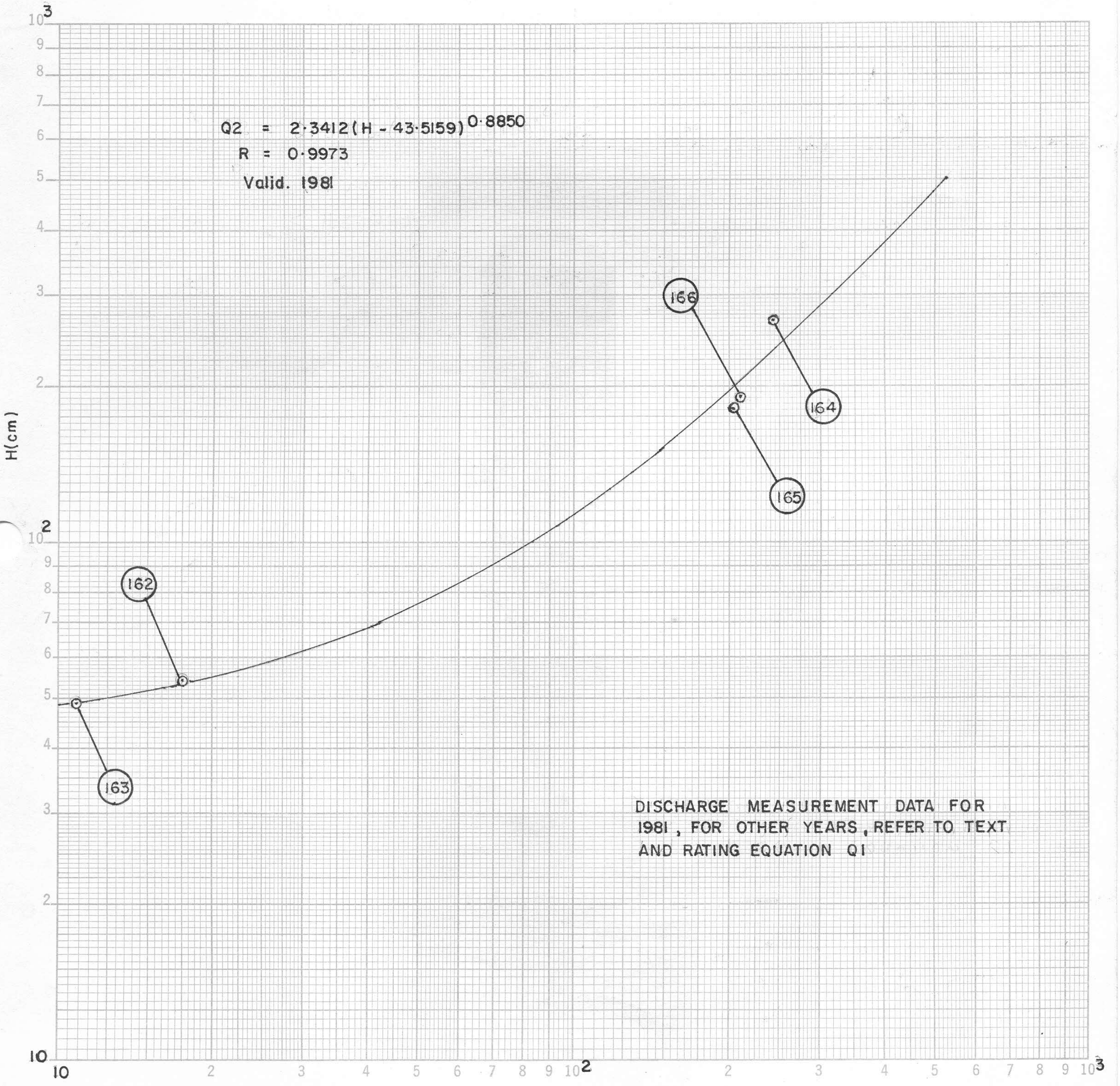


FIG. 2.2

(163) . . . Numbers as per reference

01 00 JE JENNIE ON MANO RIVER

PERIOD OF OPERATION : 1976-till now

Total number of discharge measurement data equals to 27. They originate from 1976(No.1-16), 1977(No.17-23), 1978(No.24-26) and 1979(No.27). One rating curve was fitted to these data. After plotting the data, it was decided to omit measurement Nos. 18, 19, 25 and 27 in calculations due to large deviations from any relationship line.

RATING EQUATION: $Q = 1.2274\ (H - 13.9828)^{1.0046}$

COEFF. OF CORRELATION: $R = 0.9835$

RANGE OF STAGE: $25cm \leqslant H \leqslant 666cm$

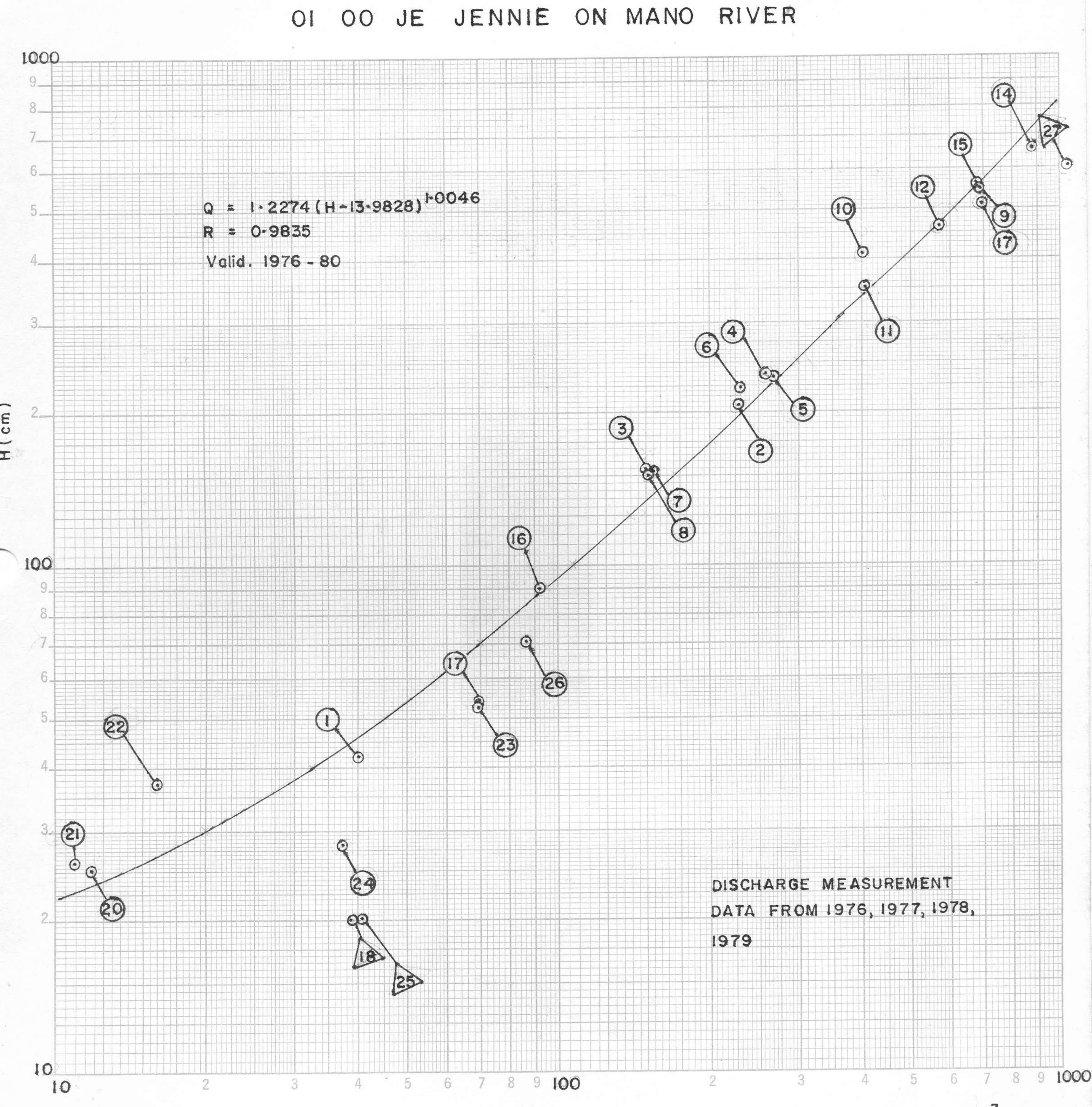

OI OO JE JENNIE ON MANO RIVER
Q = 1·2274(H-13·9828)^1·0046
R = 0·9835
Valid. 1976 - 80
DISCHARGE MEASUREMENT
DATA FROM 1976, 1977, 1978,
1979
H (cm)
Q (m3/5)
(17) denotes the point (H,Q) taken into calculation
(25) denotes the point (H,Q) omited from calculation

FIG. 2.3

01 00 BH BOLAHUN ON ZELIBA RIVER

PERIOD OF OPERATION : 1958-1973

There are 8 discharge measurements all together. Two of them were made in 1958, two in 1959, one in 1960 and three in 1961. The station was operated within the period 1958 - 1973. After plotting the data, it was decided to omit measurement Nos. 7 and 8 in rating curve derivation due to the deviations from any relationship line.

RATING EQUATION: $Q = 0.6260 (H + 0.4113)^{0.7696}$

COEFF. OF CORRELATION: R = 0.9952

RANGE OF STAGE: $12cm \leq H \leq 229cm$

0100BH BOLAHUN ON ZELIBA RIVER

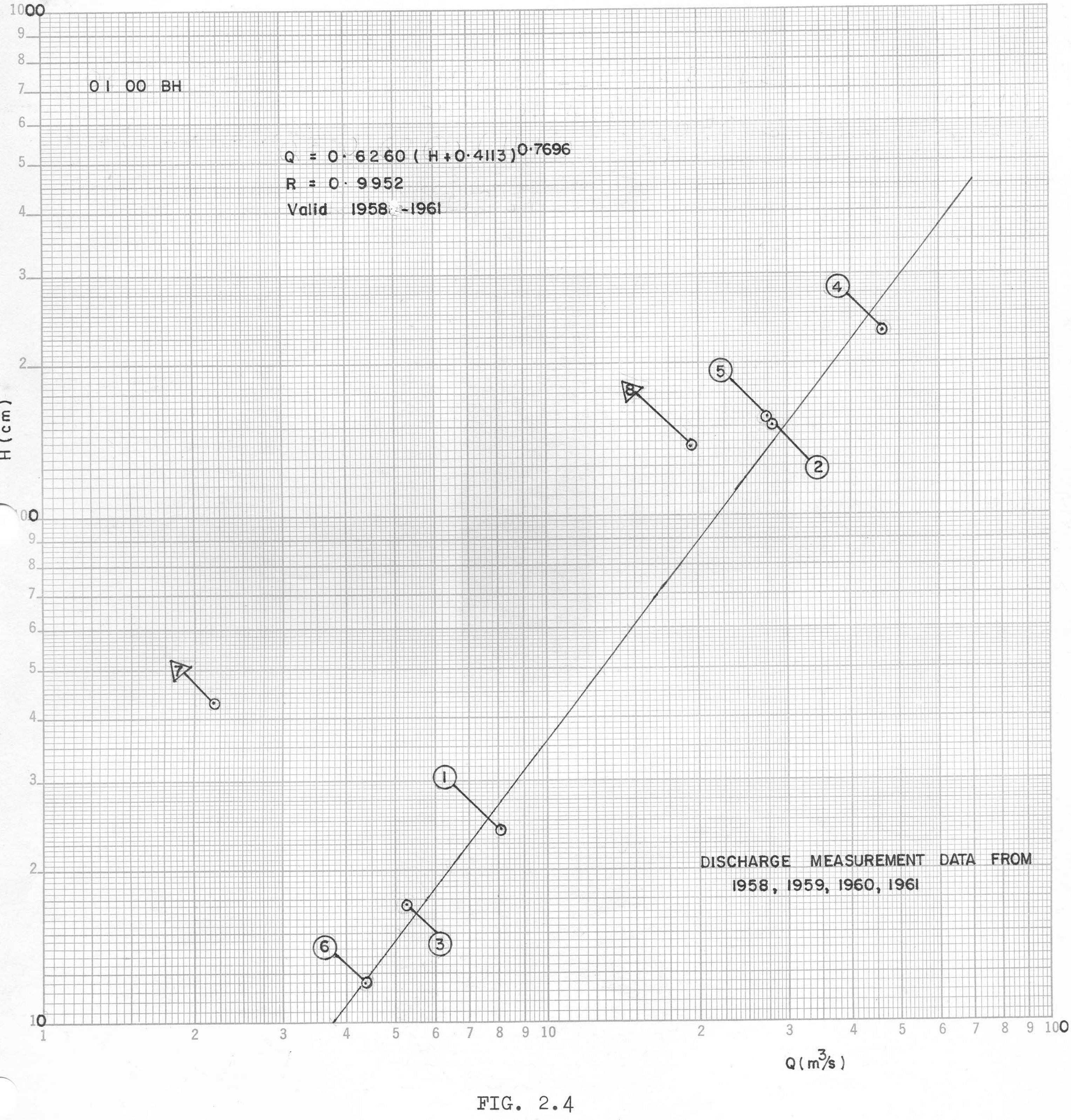


FIG. 2.4

Logarithmic, 2 x 2 Cycles

01 00 KL KOLAHUN ON KAIHA RIVER

PERIOD OF OPERATION: 1982-till now

The data is inadequate to derive the rating curve. More discharge measurements have to be made.

01 00 JT JOHNNY TOWN ON ZELIBA RIVER

PERIOD OF OPERATION: 1970-1976

The total number of discharge measurements amounts to 6. All of them were made during 1970, and accepted for rating curve derivation.

RATING EQUATION: $Q = 0.6376 \ (H - 41.6888)^{0.80686}$

COEFFICIENT OF CORRELATION: $R = 0.9988$

RANGE OF STAGE: $55cm \leq H \leq 195cm$

0100JT JOHNNY TOWN ON ZELIBA RIVER

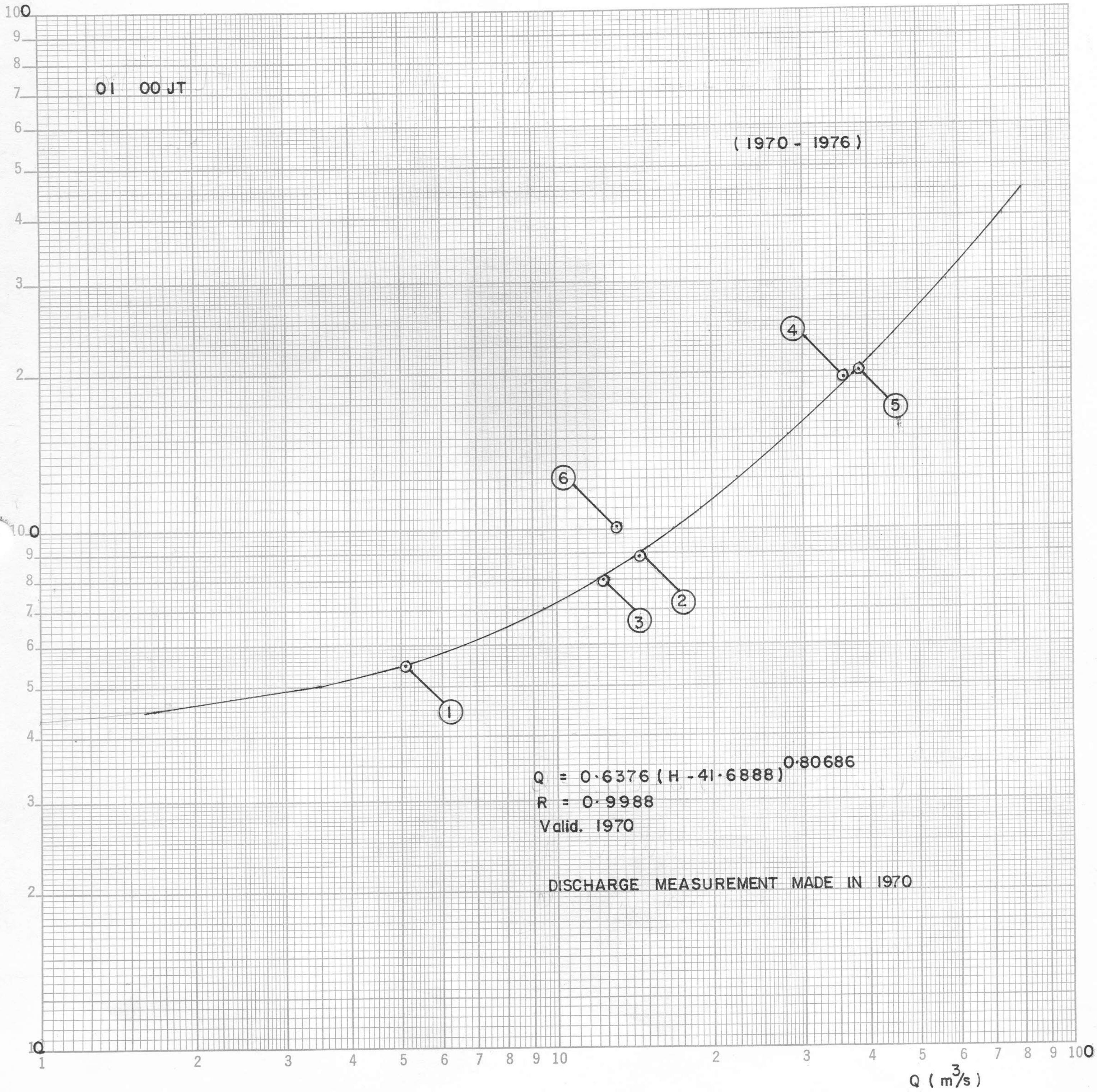


FIG. 2.5

01 00 VO VOINJAMA ON ZELIBA RIVER

PERIOD OF OPERATION: 1973-till now

The total number of discharge measurements equals to 30. After plotting these data on full-logarithmic paper, the following points were found to be erroneous and therefore excluded from further processing: No. 1, 11, 12, 23. It was noticed that the points are scattered around two curves valid within the periods Feb. 1973 - May 1974, and July 1974 - Aug. 1981 respectively. Change of gauge position in 1979, (see Remark Ref. 2 p. 28) has no visible effect on the spread of (Q,H) points. Considering this, as well as the fact that the difference in datum of two gauge positions is not known, it was decided to derive one rating curve for the entire period (July 1974 - August 1981).

I Period: Feb. 1973 - May 1974
Rating equation was derived on the basis of nine discharge measurements, i.e. point Nos. 2 - 9 and 13.

RATING EQUATION: $Q = 2.569 \times 10^{-4} (H - 57.2989)^{1.9147}$

COEFFICIENT OF CORRELATION: R = 0.9976

RANGE OF STAGE: $79cm \leq H \leq 274cm$

II Period: July 1974 - Aug. 1981
Rating equation was derived on the basis of 16 discharge measurements, i.e. the point Nos. 14 - 22 and 24 - 30.

RATING EQUATION: $Q = 9.445 \times 10^{-5} (H + 6.8300)^{2.1277}$

COEFFICIENT OF CORRELATION: R = 0.9581

RANGE OF STAGE: $43cm \leq H \leq 269cm$

OIOOVO VOINJAMA ON ZELIBA

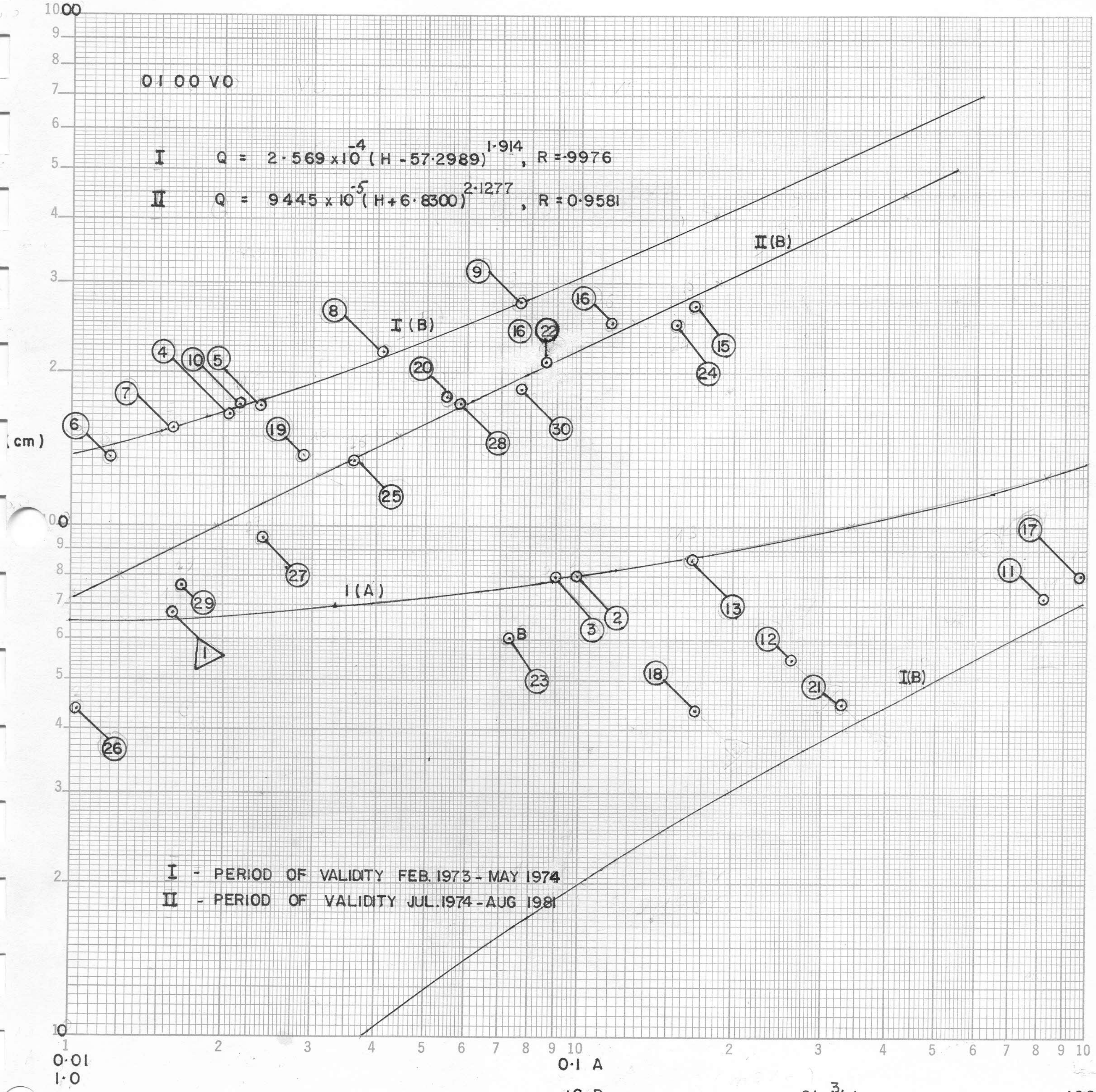


FIG. 2.6

01 00 BO(T) BOLAHUN ON WAWO CREEK

PERIOD OF OPERATION:1958-1973, 1982-till now

Nine out of ten measurements performed during 1958 - 1961 were accepted for derivation of the Rating equation. The measurement No. 5 was excluded due to the lack of corresponding guage reading.

RATING EQUATION: $Q = 3.492 \times 10^{-3}(H + 5.1349)^{1.4928}$

COEFFICIENT OF CORRELATION: R = 0.9931

RANGE OF STAGE: $12cm \leq H \leq 108cm$

PERIOD: 1982 - 1983

There are two discharge measurements only (No. 11 and 12) made during this period. To derive the rating curve in such case, the same flow conditions as during 1958 -61 were assumed. Accordingly, the rating curve for 1982 - 83 differs from the previous one only due to the difference in Water gauge datum. This difference was estimated by means of two above mentioned results of discharge measurements (point Nos. 11, 12) and the rating equation for 1958 -'61.

$$\Delta_{11} = H_{11} - H(Q_{11}) = 158 - 58 = 100$$

$$\Delta_{12} = H_{12} - H(Q_{12}) = 129 - 47.8 = 81.4$$

where $H(Q_{ii})$ - the gauge height corresponding to Q_{ii} on the Rating Curve (1958 -'61)

$$\Delta\ MEAN = 0.5(\Delta_{11} + \Delta_{12}) = 90.7$$

A rough estimate of the Rating equation for the 1982 - 83 period:

$$Q = 3.492 \times 10^{-3}(H - 85.56)^{1.4928}$$

It is highly recommended to improve the equation by means of more discharge measurements.

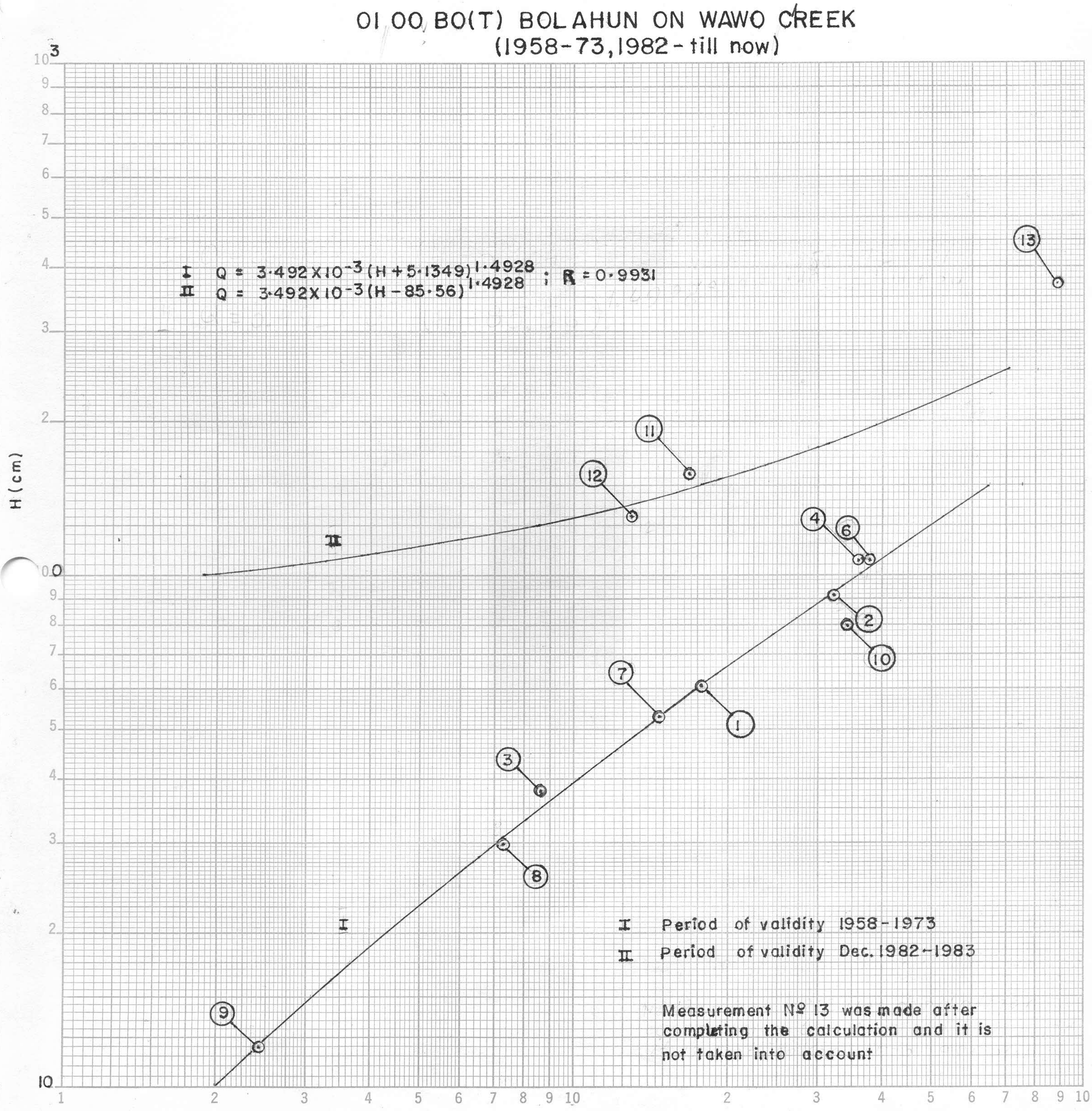

01 00 BO(T) BOLAHUN ON WAWO CREEK
(1958-73, 1982 - till now)
I Q = 3·492 X 10^-3 (H + 5·1349)^1·4928 ; R = 0·9931
II Q = 3·492 X 10^-3 (H - 85·56)^1·4928
H (cm)
I Period of validity 1958-1973
II Period of validity Dec. 1982-1983
Measurement Nº 13 was made after completing the calculation and it is not taken into account
Logarithmic, 2 x 2 Cycles

FIG. 27

01 L3 WO(T) WOLOGIZI ON MASSOH CREEK

PERIOD OF OPERATION: 1978-1979

There are ten recorded flow measurements; however, five of these (#6 to #10) were conducted for the same value of stage. Variations in calculated discharge and cross-sectional area were considered to be due to computational errors. A mean value of flow was therefore assigned to the recorded water level; a mean cross-sectional area was similarly assigned.

As the measurement of 7 November, '78 was unreferenced to a gauge height, it could not be included in the derivation of the rating equation. Accordingly, only five points were used in defining the rating curve. It should be noted that data considered here are undocumented as per reference 2. They have only recently been discovered in the LHS Archives.

RATING EQUATION: $Q = 3.0179\ (10^{-3})\ (H - 82.9240)^{3.1179}$

COEFFICIENT OF CORRELATION: $R = 0.9761$

RANGE OF STAGE: $87\text{cm} \leq H \leq 101\text{cm}$

The validity of above equation is questionable, considering the nature of the data. It is interesting to note that stage as low as 200cm will suggest streamflow rate of about 8,500 cumecs. This is just why it is recommended to conduct more measurements at this site.

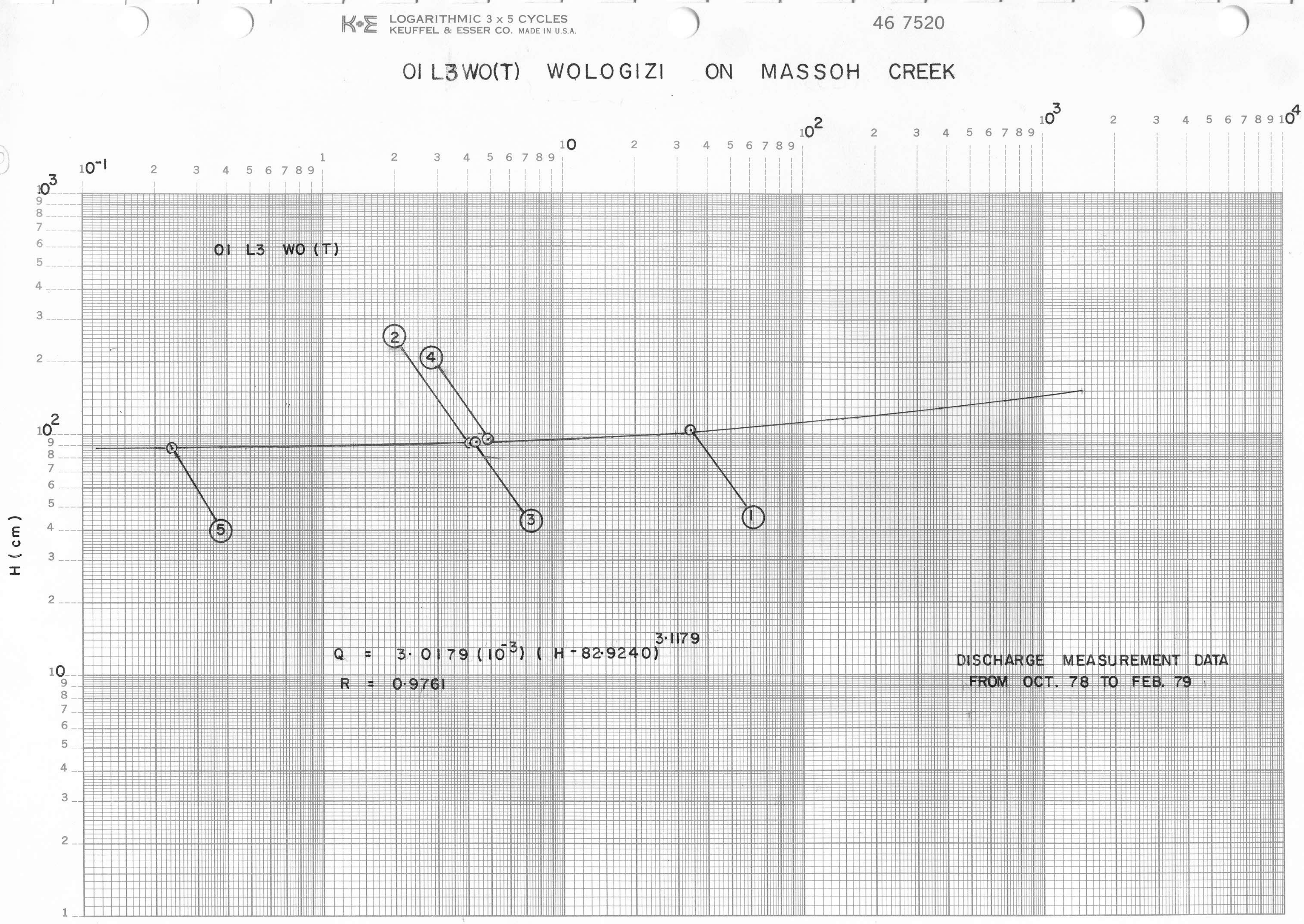
TABLE 2.2 DISCHARGE MEASUREMENT DATA

01 L3 WO(T)

WOLOGIZI ON MASSOH CREEK

PERIOD OF OPERATION: 1978 - 1979

NO	DATE	H (cm)	Q (m^3/s)	A (m^2)	PERFORMED BY	REMARKS
1	21 OCT. 78	101	33.221		LHS	
2	8 NOV. 78	92	4.067	3.47	"	
3	9 NOV. 78	93	4.313	5.10	"	
4	10 NOV. 78	96	4.847	5.05	"	
5	7 DEC. 78	-	0.400	5.05	"	
6	2 FEB. 79	87	0.166	4.249	"	Old site
7	3 FEB. 79	87	0.181	4.291	"	Old site
8	3 FEB. 79	87	0.460	3.685	"	New site
9	4 FEB. 79	87	0.166	4.295	"	Old site
10	4 FEB. 79	87	0.187	2.425	"	New site



LOGARITHMIC 3 x 5 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 7520
OI L3WO(T) WOLOGIZI ON MASSOH CREEK
OI L3 WO (T)
Q = 3·0179 (10^-3) (H - 82·9240)^3·1179
R = 0·9761
DISCHARGE MEASUREMENT DATA
FROM OCT. 78 TO FEB. 79
H (cm)
Q (m3/s)

FIG. 2.8

02 01 BE BENDUMA ON MAFFA RIVER

PERIOD OF OPERATION: 1975-till now

There are 2 measurement points as per reference 2. All were conducted by the Liberian Hydrological Service. A new measurement was recently made:

NO.	DATE	H (cm)	Q (m^3/s)	A (m^2)	PERFORMED BY	REMARKS
3	Dec. 14,'83	96	4.342	11.06	LHS	inconsistent with No. 2.

Because the data set is limited to 3 points and considering the slight incoherence between D.M. Nos. 2 and 3, use of the statistical approach is still possible, but not advisable as the derived relationship may tend to be misleading. Since discharge measurement notes are available for No. 3, only this measurement was used for hydraulic derivation of the rating curve. It should be noted that this rating curve is limited in application. In effect it covers the gauge height interval 0cm $\leq$ H $\leq$ 96cm.

Below skeleton rating table was obtained using version 3 of the "BED PAR" computer programme (Ref. 3).

TABLE 2.3 RATING TABLE AS PER VERSION III of "BED PAR" PROGRAM

02 01 BE BENDUMA ON MAFFA RIVER

GH(cm)	$\sum_{i=1}^{n} (A_i (RH_i)^{2/3})$	Q(m^3/s)
96	9.2843	4.342
90	8.1146	3.795
80	6.3337	2.962
70	4.7640	2.228

TABLE 2.3 (cont'd)

GH(cm)	$\sum_{i=1}^{n} (A_i(RH_i)^{2/3})$	$Q(m^3/s)$
60	3.4143	1.597
50	2.2859	1.069
40	1.3753	0.643
30	0.6937	0.324
20	0.2363	0.111
10	0.0196	0.009
0	0.0000	0.000

The slope roughness parameter was calculated to be $D = Q/\ A{*}RH^{2/3}$ = 4.342/9.2843 = 0.4677. This D-value was used to estimate those to be expected for gauge heights for D.M. Nos. 1 and 2, as are tabulated below:

NO.	DATE	GH (cm)	Q (m^3/s)	A (m^2)	D $(m^{1/3}/s)$
1	May 18, '82	68	1.600	6.88	0.3313
2	Jun.17, '82	97	3.430	10.90	0.4726
3	Dec.14, '83	96	4.342	11.06	0.4677
				MEAN	0.4239

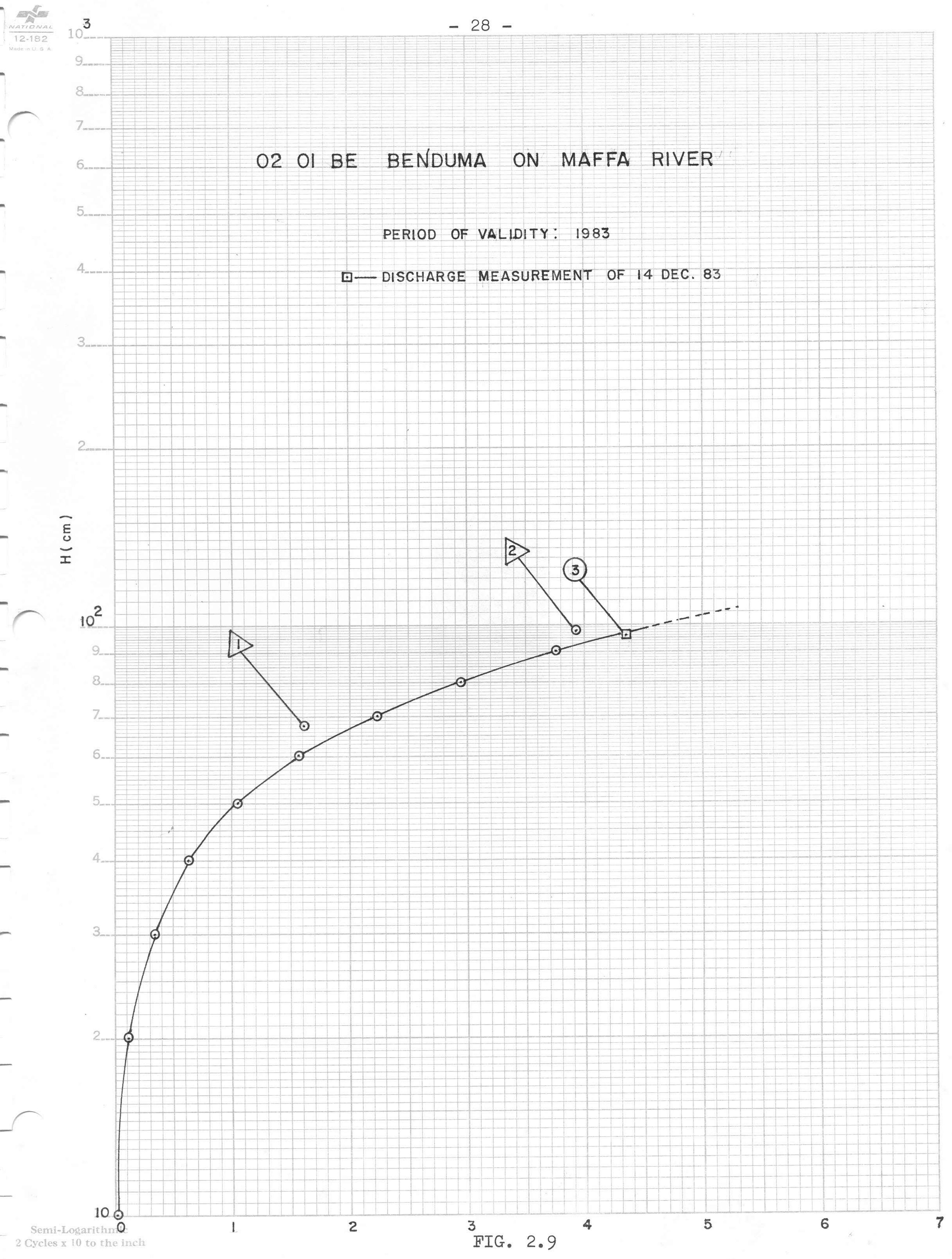

NATIONAL
12-182
Made in U.S.A.
02 01 BE BENDUMA ON MAFFA RIVER
PERIOD OF VALIDITY: 1983
DISCHARGE MEASUREMENT OF 14 DEC. 83
H (cm)
10^3
10^2
10
1
2
3
0
1
2
3
4
5
6
7
Semi-Logarithmic
2 Cycles x 10 to the inch

FIG. 2.9

02 05 RO ROBERTSPORT ON FASA CREEK

PERIOD OF OPERATION: 1974-till now

There are ten measurements all made during Feb.'74 - Jan.'75. Plotting them on full logarithmic paper did not reveal any high deviation. Therefore all of them were taken as the input data for statistical derivation of the rating equation.

Accordingly:

RATING EQUATION: $Q = 9.1565 \times 10^{-11}(H - 324.1673)^{5.2234}$

COEFFICIENT OF CORRELATION: $R = 0.9982$

RANGE OF STAGE: $352\text{cm} \leqslant H \leq 404\text{cm}$

Since the concrete weir stabilizes the cross-section of the creek, when operating within the modular range, the rating curve can be assumed to be valid in the period 1974 - 1980, i.e. till the gauge was destroyed.

The difference in datum of old and new staff gauge is not known. There are records of discharge measurements after 1980. Because of this, it is not possible to derive the current rating curve based on the available information.

0205 RO ROBERTSPORT ON FASA CREEK

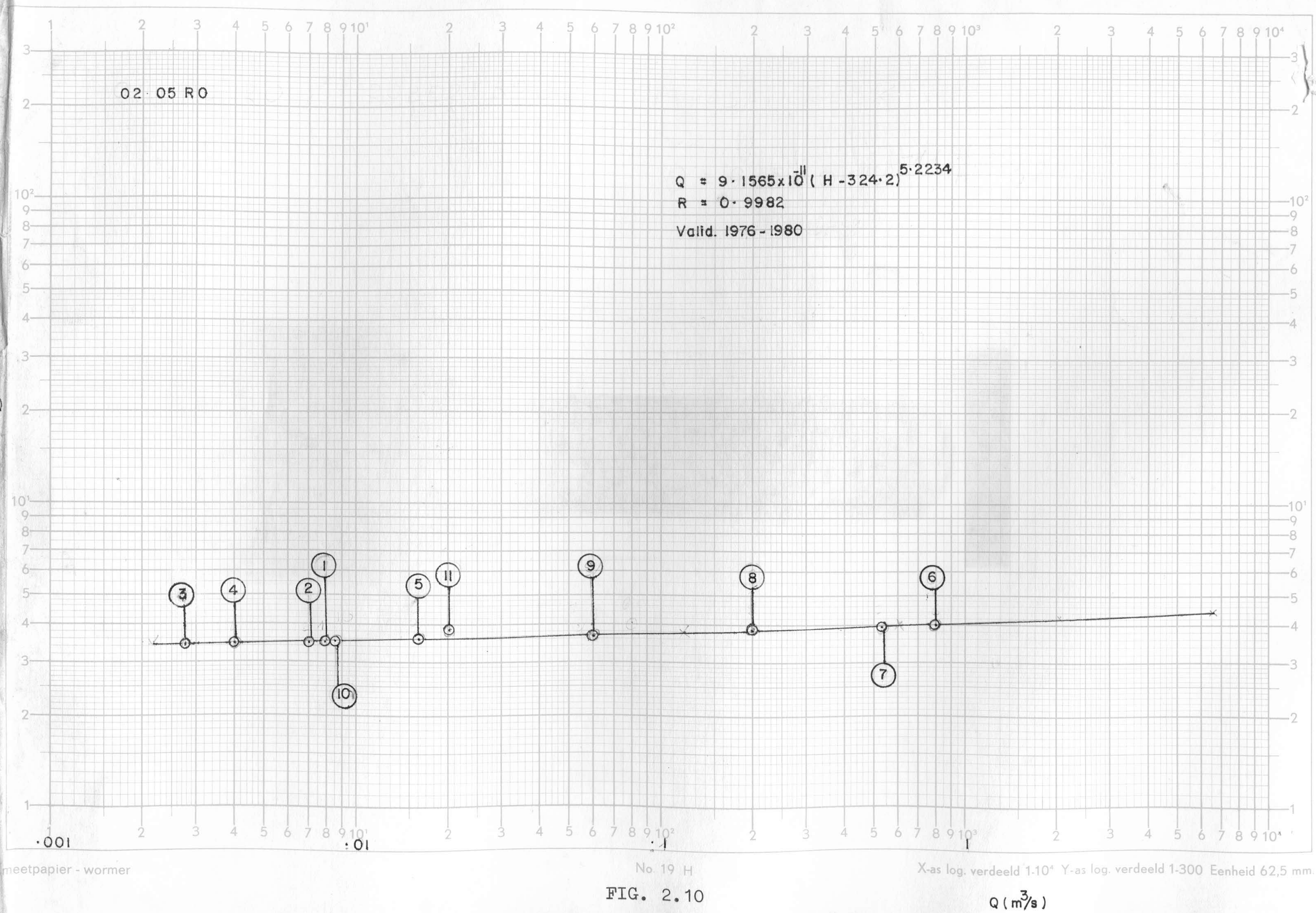


FIG. 2.10

03 00 DU DUOGOMAI ON LOFA RIVER

PERIOD OF OPERATION: 1970-till now

There are twelve discharge measurements in all, of which seven were made in 1970, 1 - 1973, 3 - in 1981, 1 - in 1982. They were plotted on full log-paper. All these points form one line and no big deviations from it were found. This is why only one curve was fitted to all data.

Rating Curve Equation

RATING EQUATION: $Q = 5.669 \times 10^{-3}(H - 41.9097)^{1.8086}$

Q in m^3/s, H in cm

COEFFICIENT OF CORRELATION: R = 0.9988

RANGE OF STAGE: $78\text{cm} \leq H \leq 400\text{cm}$

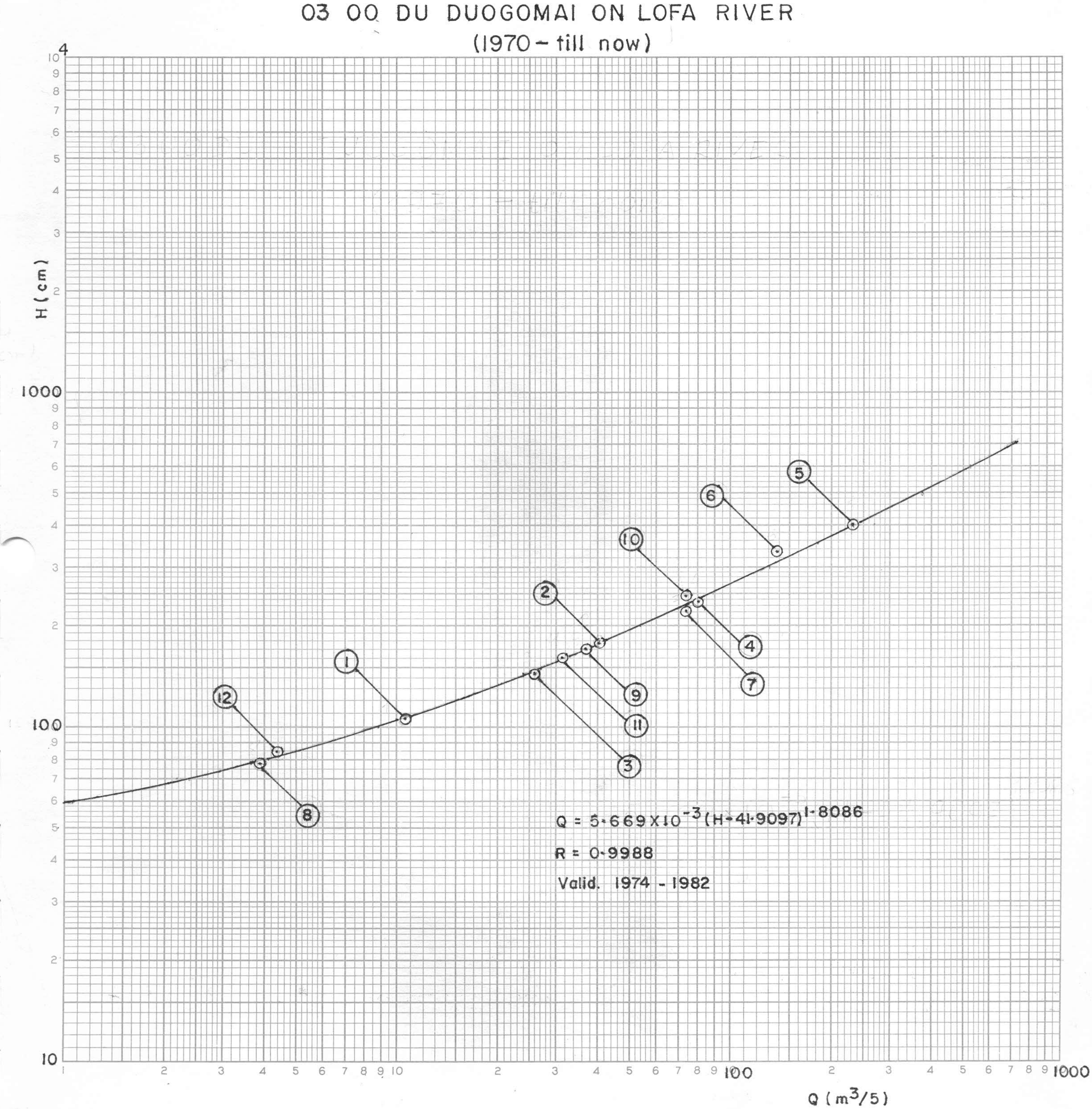

03 00 DU DUOGOMAI ON LOFA RIVER
(1970 – till now)
H (cm)
Q (m3/5)
Q = 5·669 x 10^-3 (H-41·9097)^1·8086
R = 0·9988
Valid. 1974 - 1982
10
100
1000
10^4
1
10
100
1000
1
2
3
4
5
6
7
8
9
10
11
12

FIG. 2.11

03 L3 LU LUYEMA ON LAWA RIVER

PERIOD OF OPERATION: 1970-till now

There are all together 15 discharge measurements. These may be organized as follows:

7	made	in	1970
2	made	in	1979
3	made	in	1981
2	made	in	1982
1	made	in	1983

One rating curve is valid for the entire period of operation. Measurement No. 13 was eliminated because it was wrong. On account of the big dispersion of two lowest points on the plot, i.e. No. 1 and No. 2, accuracy of the Rating Curve in this zone can be low. Additional measurements below 50cm gauge height are recommended.

RATING EQUATION: $Q = 2.0208 \times 10^{-3}(H + 44.4495)^{1.7666}$
where Q in m^3/s, H in cm.

COEFFICIENT OF CORRELATION: 0.9676

RANGE OF DISCHARGE MEASUREMENTS: $25cm \leq H \leq 316cm$

03 L3 LU LUYEMA ON LAWA RIVER

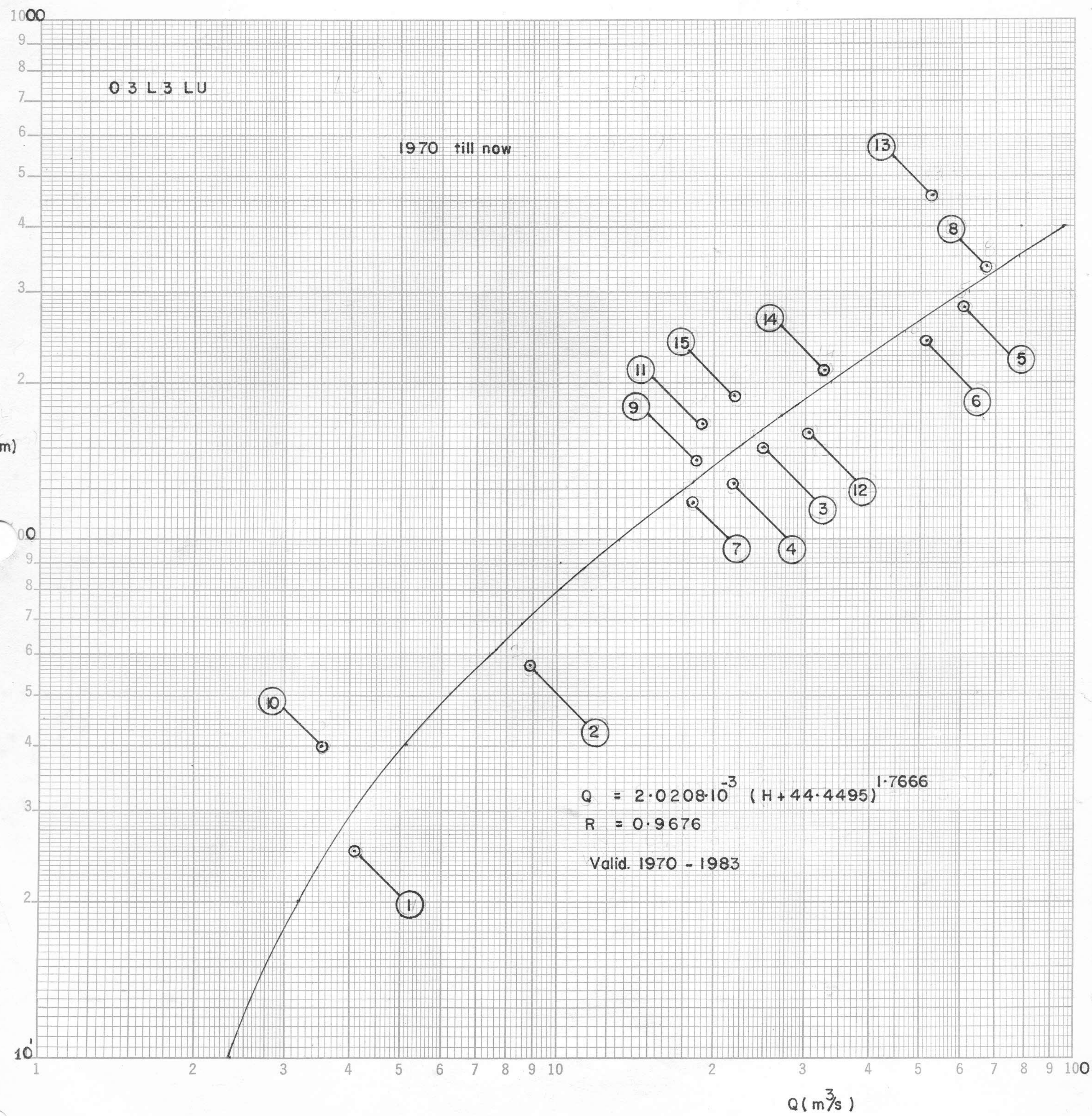


FIG. 2.12

05 00 MC MOUNT COFFEE ON ST. PAUL RIVER

PERIOD OF OPERATION: 1958-1966

There are all together 15 discharge measurements of which

	5	were	made	in	1958
	3	were	made	in	1959
	4	were	made	in	1960
	2	were	made	in	1961
and	1	was	made	in	1962

One rating curve was fitted to these data. Measurement No. 6 was excluded from calculation due to the lack of the gauge height in the discharge measurement notes. All points on the diagram form one line. There are big random (non regular) differences between Gauge Heights given in the Discharge Measurement Notes and those published in the Hydrological Data Book; (see Ref. (2), page 34). They can be explained neither by gauge reading error nor by unsteady state in the river.

RATING EQUATION: $Q = 5.6584 \times 10^{-4}(H - 235.4403)^{2.4212}$
where Q in m^3/s, H in cm.

COEFFICIENT OF CORRELATION: R = 0.9892

RANGE OF DISCHARGE MEASUREMENTS: $347cm \leq H \leq 658cm$

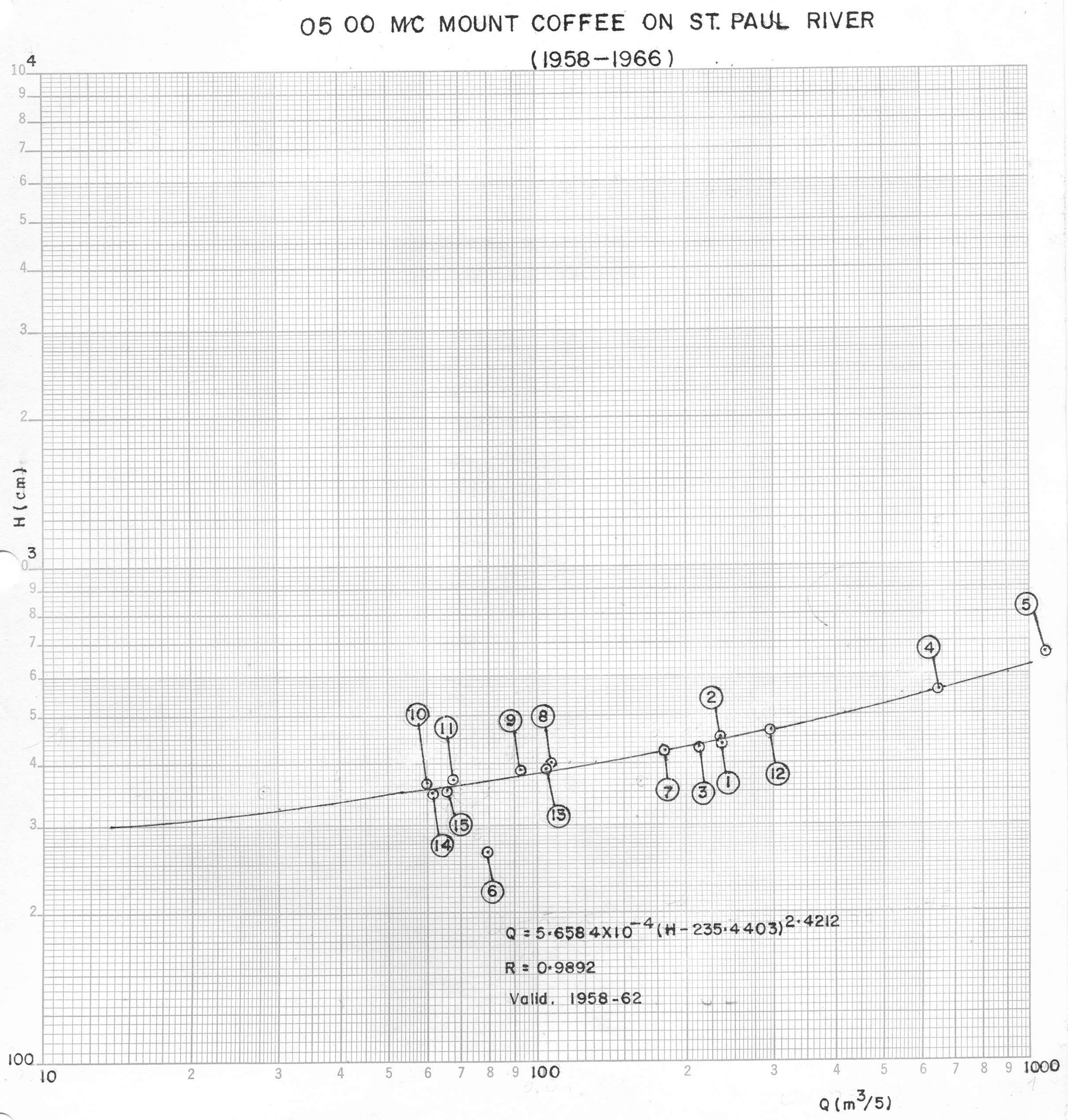


FIG. 2.13

Logarithmic, 2 x 2 Cycles

05 00 HE HEINDI ON ST. PAUL RIVER

PERIOD OF OPERATION: 1973-till now

There are all together 3 discharge measurements made during 1980 and 1981.

NO	DATE	GAUGE HEIGHT GH (m)	DISCHARGE Q (m^3/s)	AREA A(m^2)
1	FEB. 23, '80	0.59	43.31	-
2	NOV. 13, '81	1.14	174.28	359
3	May 20, '81	0.12	54.51	159

The first two are listed in the Ref. 2 (p. 35), while the third one was found only recently in the LHS Archive. The Rating Equation was derived by means of the hydraulic approach. The way of the computation and the input - output data are given in the "Rating Curves of Liberian Rivers, Part III: Hydraulic Estimation". Therefore the final result i.e. the rating curve is as shown in the report, (p. 28).

RATING TABLE

GH (m)	TOTAL $A \times RH^{2/3}$ (m8/3)	Q (m3/s)
1.14	516.0922	160.1
1.1	498.0641	154.5
1.0	453.7193	140.7
0.9	410.9685	127.5
0.8	371.1201	115.1
0.7	334.4737	103.7
0.6	302.3646	93.79
0.59	300.4352	93.19
0.50	273.3192	84.78
0.40	247.4704	76.76
0.30	224.0952	69.51
0.20	203.2320	63.04
0.12	189.0848	58.65
0.10	185.5480	57.56
0.00	170.9080	53.02
- 0.10	160.6165	49.82
- 0.20	152.7403	47.38
- 0.30	145.9427	45.27
- 0.40	139.6307	43.31
- 0.50	133.7199	41.48
- 0.60	128.2083	39.77
- 0.70	123.8918	38.43
- 0.80	121.4505	37.67
- 0.90	119.5679	37.09
- 1.00	115.9425	35.96

The values of $(A \times RH^{2/3})$ for GH's lower than -1m are given as the output data of the programme only. Ref. 3.

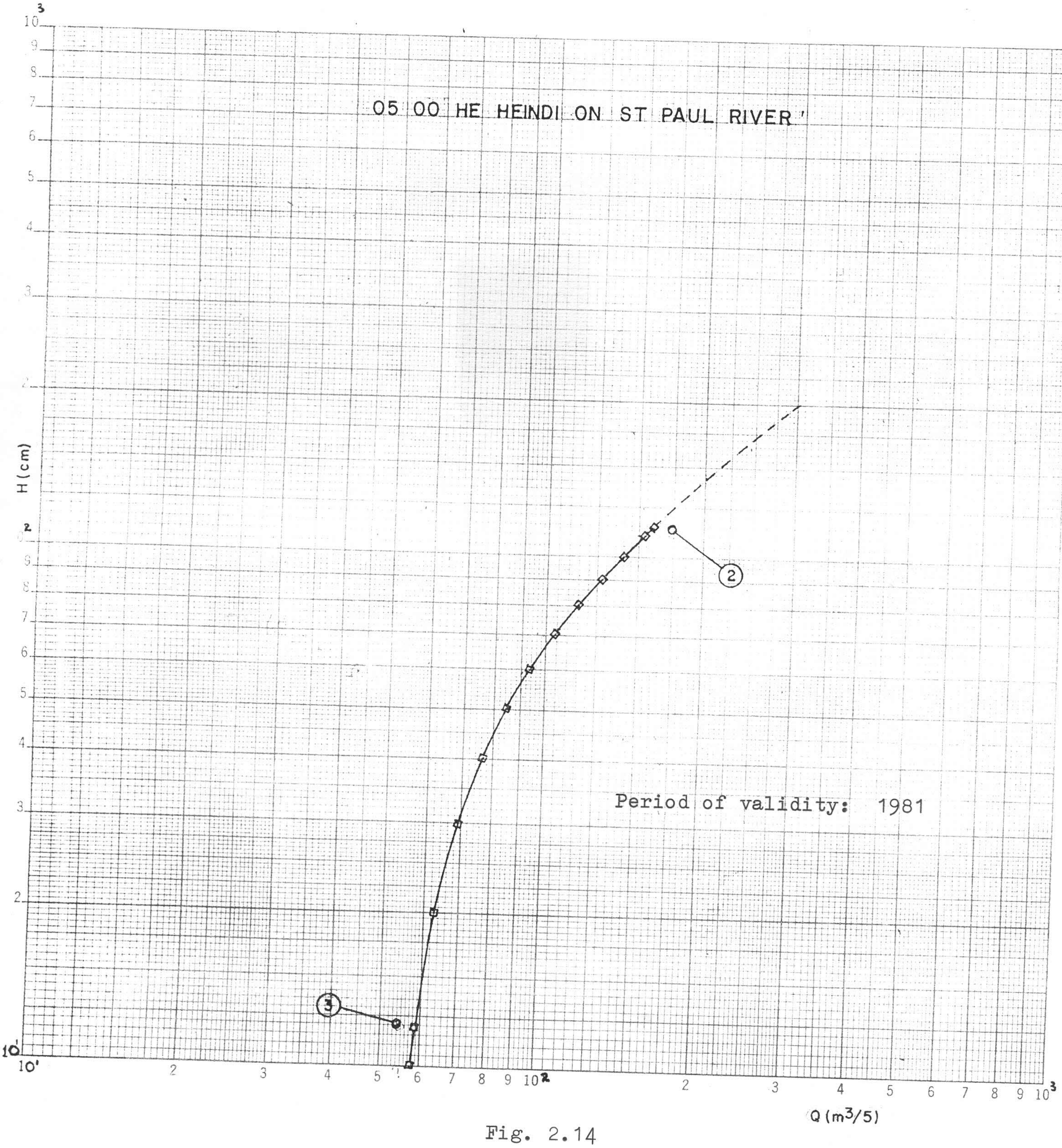

05 00 HE HEINDI ON ST PAUL RIVER
H (cm)
Q (m3/5)
Period of validity: 1981
2
3

Fig. 2.14

05 00 WB WALKER BRIDGE (GWEYEA) ON ST. PAUL RIVER

PERIOD OF OPERATION: 1958-till now

There are all together 24 discharge measurements of which

4	made	in	1958
5	made	in	1959
2	made	in	1960
3	made	in	1961
2	made	in	1974
1	made	in	1977
2	made	in	1978
1	made	in	1980
3	made	in	1981

Measurement No. 18 was excluded from the input data as the corresponding gauge reading was missing. All measurement points (Q_i, H_i, i = 1, 2, ..., 24) form one line on full logaritmic paper. Therefore there is no justification to derive separate Rating Curve for different periods as was previously done while preparing the Hydrological Data Book from inception - 1976.

RANGE OF DISCHARGE MEASUREMENTS: $-26cm \leq H \leq 171cm$

There are two points, (no. 10 and No. 13), which would cause high convexity of the Rating Curve. Such rapid change of rating curve derivative (slope) may result from complex channel geometry with deep and narrow main channel. However, it may also result from erroneus data. The attempt was made to approximate the rating curve by means of two limbs joined at H = 25cm level. The lower limb was to be matched to three points, i.e. one in the junction and two points from measurements. The attempt failed as the only solution for the B-parameter was plus infinity. In the conclusion points No. 10 and No. 13 were omitted from further processing. They were considered to be erroneus. The validity of this equation will be checked by future discharge measurement data.

THE RATING EQUATION: $Q = 5.1169 \times 10^{-2} (H + 18.46337)^{1.8007}$

where Q in m^3/s, H in cm

valid 1958 - 1981

COEFFICIENT OF CORRELATION: R = 0.9812

05 00 WB WALKER BRIDGE (GWEYEA) ON ST. PAUL RIVER

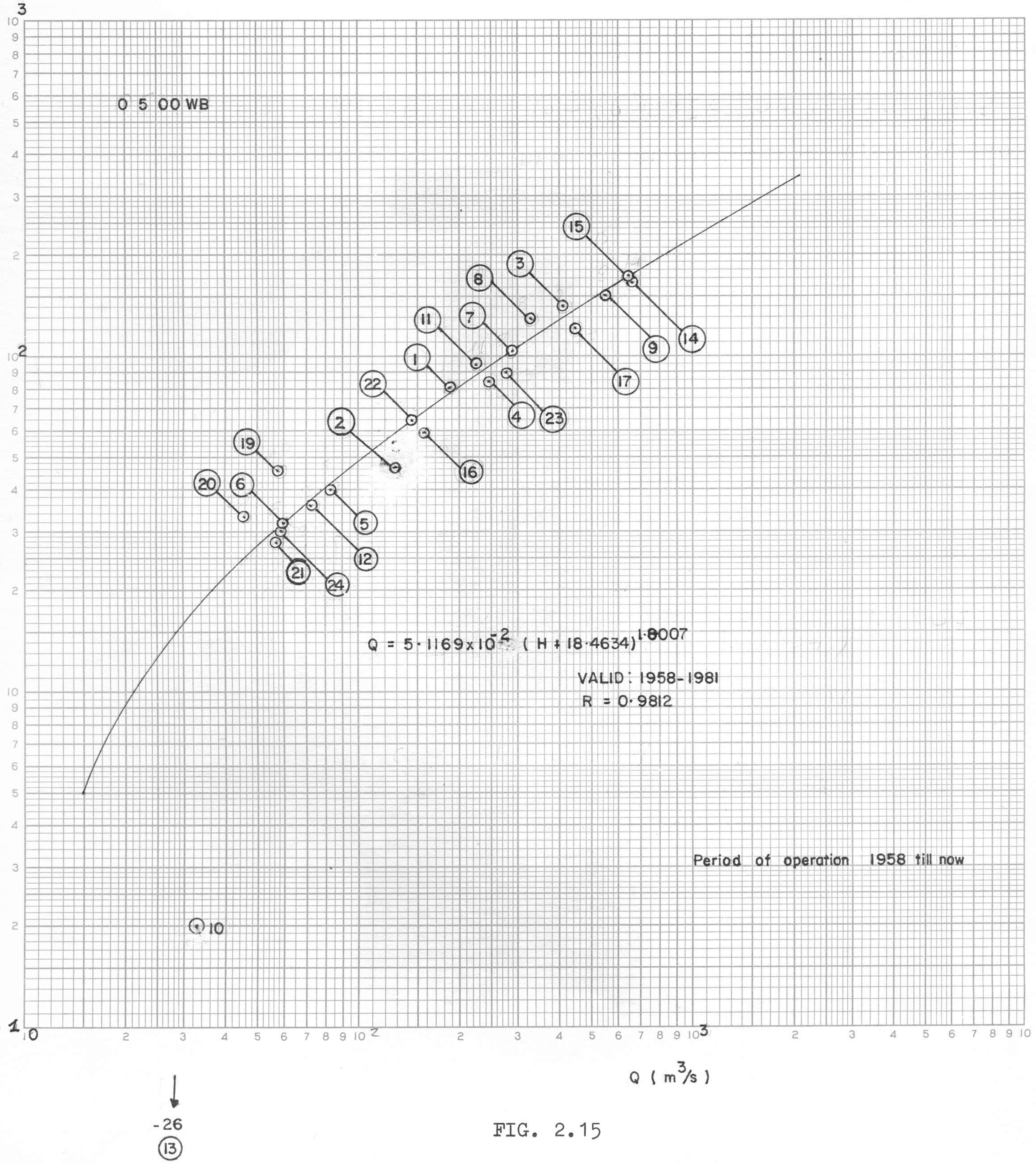


FIG. 2.15

05 00 MC(T) MT. COFFEE ON QUAIHN (KOIN) CREEK

PERIOD OF OPERATION: 1980-till now

Since there is only one discharge measurement, and considering that it was made during the dry season it is impossible to derive the Rating Curve.

05 R3 BY **BELLE YALLA ON TUMA CREEK**

PERIOD OF OPERATION: 1967-1968

Ten measurements have been recorded for this station, and they span the period from August, 1967 to November, 1968. The first three measurements were conducted by SE, the others by CTM. Measurement number 3 dated 21 November, 1967 was not included in the derivation of the rating equation since it is obviously wrong. It is noted that the flow measurement notes for all these points are not available in LHS files.

RATING EQUATION: $Q = 0.0182\ (H - 44.1928)^{1.3666}$

COEFFICIENT OF CORRELATION: $R = 0.9972$

RANGE OF STAGE: $76\text{cm} \leq H \leq 550\text{cm}$

05 R3 BY BELLE YALLA ON TUMA CREEK

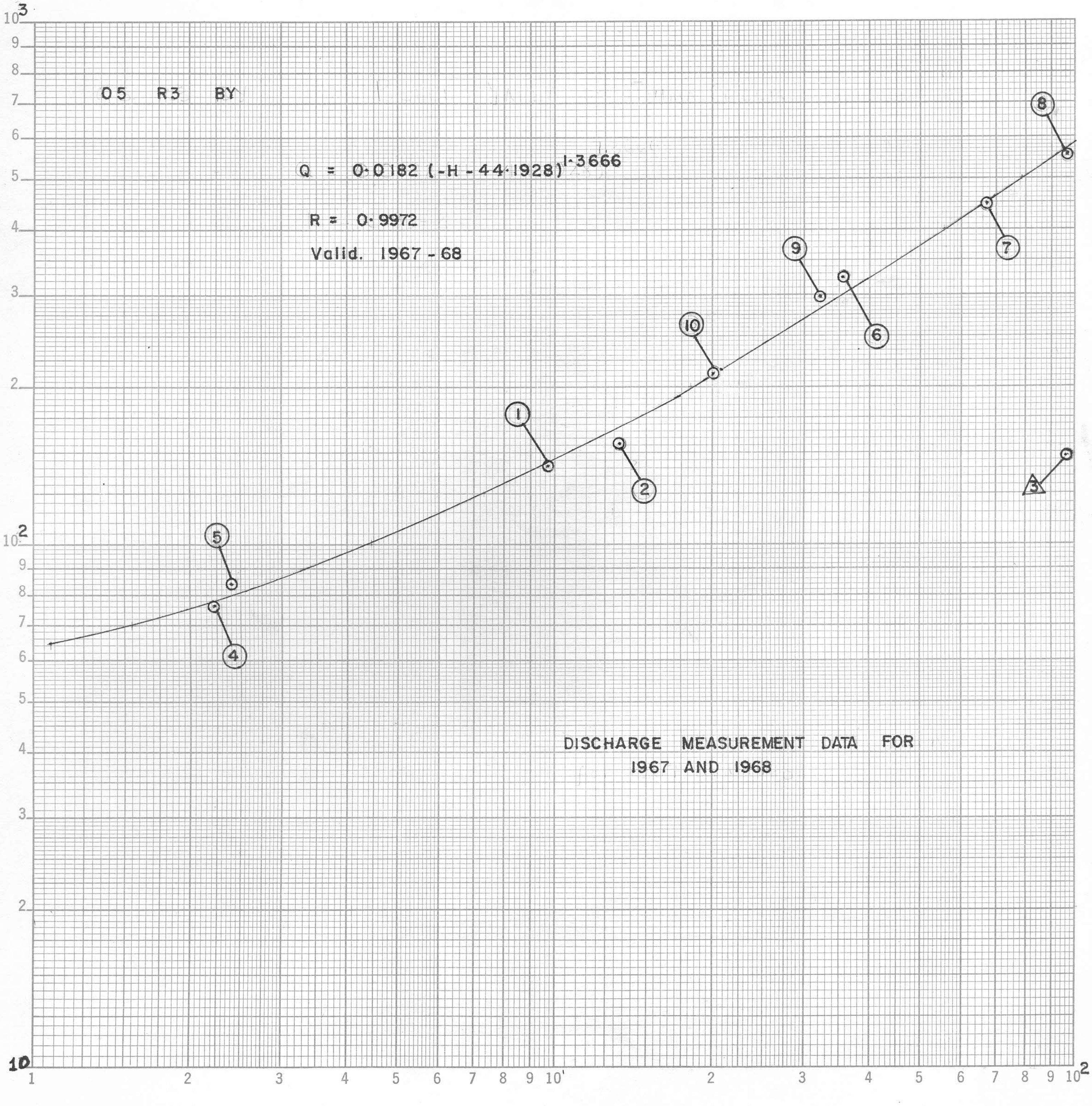


FIG. 2.16

(6) .... Denotes point (H,Q) used in calculation

(3) (triangle) .... (H,Q) Omitted from calculation

05 R3 PA **PALAKOLE ON TUMA CREEK**

PERIOD OF OPERATION: 1967-1968

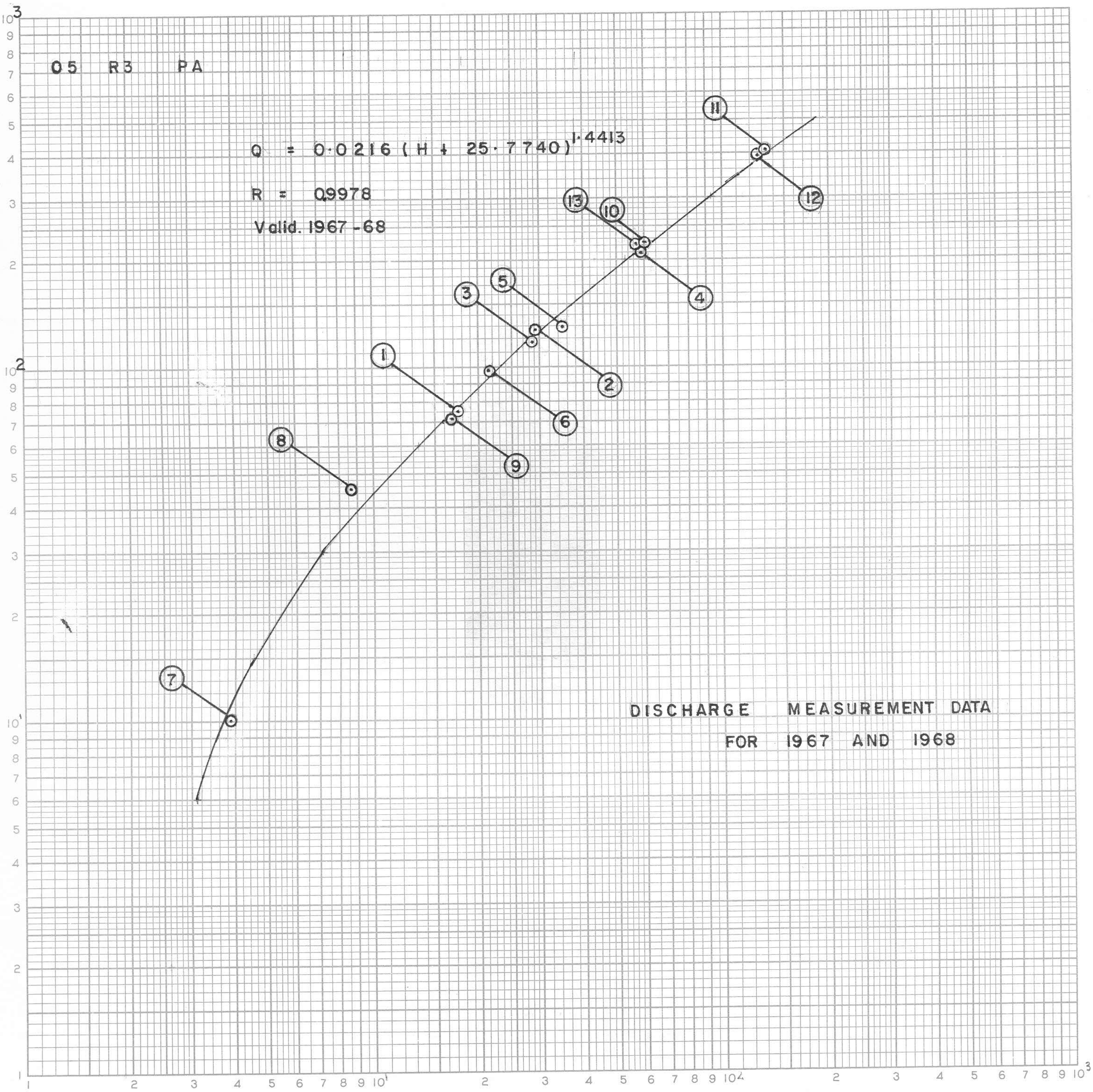
Flow measurement notes for all 13 measurements at this station are not available in the LHS files. These measurements span the period from July 1967 to November 1968. Only three of these measurements were conducted by **SE** while all others were due to CTM. All thirteen points (Q, H) were employed in the computer programme for derivation of the rating equation;

RATING EQUATION: $Q = 0.0216\ (H + 25.7740)^{1.4413}$

COEFFICIENT OF CORRELATION: R = 0.9978

RANGE OF STAGE: $10\text{cm} \leq H \leq 405\text{cm}$

05 R3 PA PALAKOLE ON TUMA CREEK



(1) .... Point (H, Q) used in calculation

FIG. 2.17

05 R4 GB GBAKWELLIE ON VAI RIVER

PERIOD OF OPERATION: 1967-1968

Twenty recorded discharge measurements have been made at this site. The first four of these were conducted by SE while all others are due to CTM. Measurement numbers 4 and 6 were omitted in the derivation of the rating equation for obvious reasons (refer to the rating curve). No discharge measurement notes are available at LHS concerning these 20 measurements, which span the period from July, 1967 to November, 1968.

RATING EQUATION: $Q = 0.3923\ (H - 96.3905)^{1.1634}$

COEFFICIENT OF CORRELATION: $R = 0.9961$

RANGE OF STAGE: $113\text{cm} \leq H \leq 568\text{cm}$

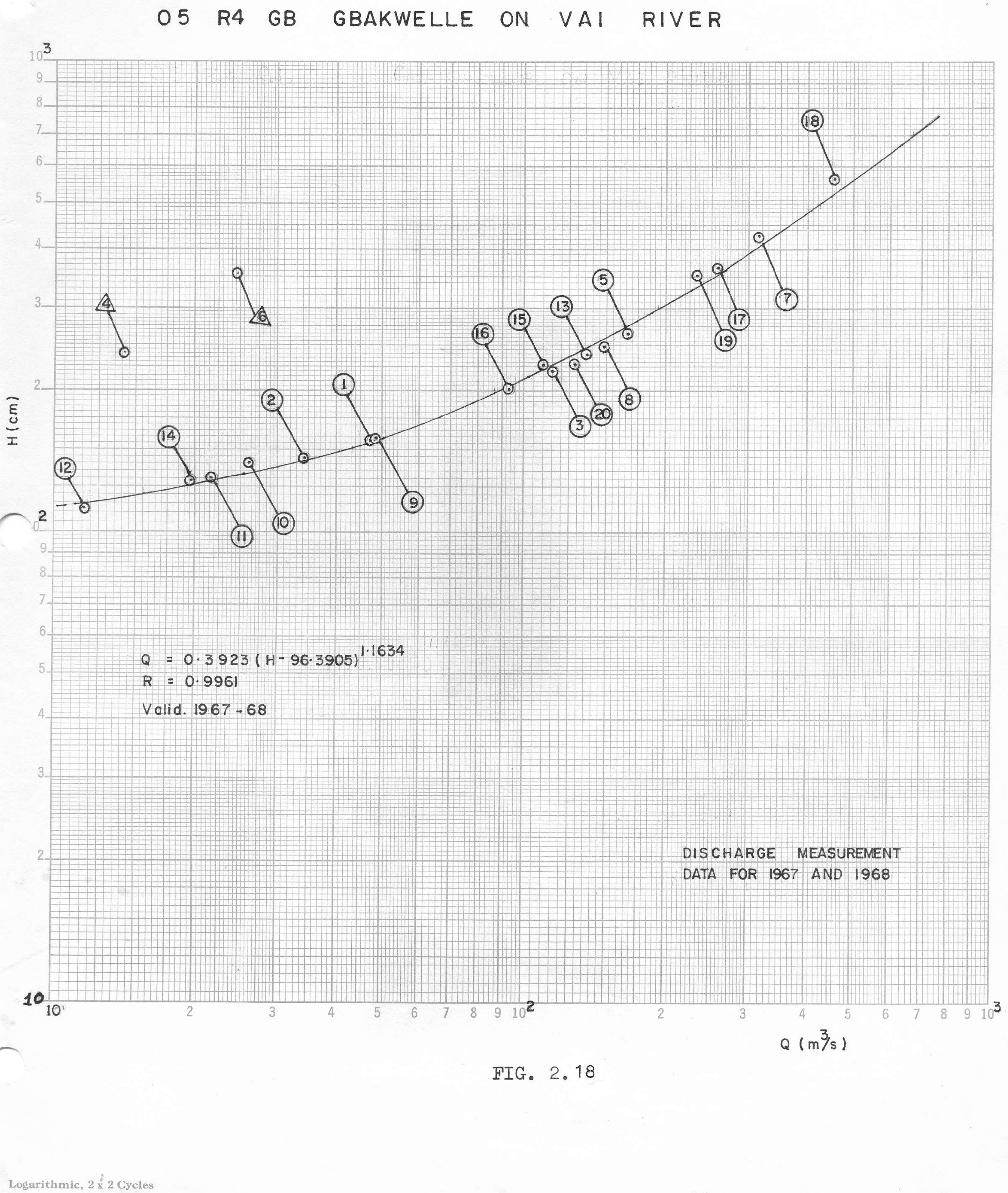

05 R4 GB GBAKWELLE ON VAI RIVER
H (cm)
Q (m³/s)
Q = 0·3923 (H - 96·3905)^1·1634
R = 0·9961
Valid. 1967 - 68
DISCHARGE MEASUREMENT
DATA FOR 1967 AND 1968
Logarithmic, 2 x 2 Cycles

FIG. 2.18

05 R5 ZO(T) **ZORZOR ON BAMAYEA CREEK**

PERIOD OF OPERATION: 1978-till now

There are nine flow measurement points (Q,H) for this site. Measurement number 9 was omitted in the derivation of the rating equation. This led to an increase (3%) in the coefficient of determination, indicating that the point may not have been very wrong. All measurements have been conducted by the LHS and span the period from October, 1978 to October, 1983. The datum over this measurement period has been the same, all measurements having been taken from the cross-section at the staff gauge.

RATING EQUATION: $Q = 4.6830\ (10^{-5})\ (H - 25.9065)^{2.2931}$

COEFFICIENT OF CORRELATION: $R = 0.9699$

RANGE OF STAGE: $34cm \leq H \leq 81cm$

05 R5 ZO(T) ZORZOR ON BAMAYEA CREEK

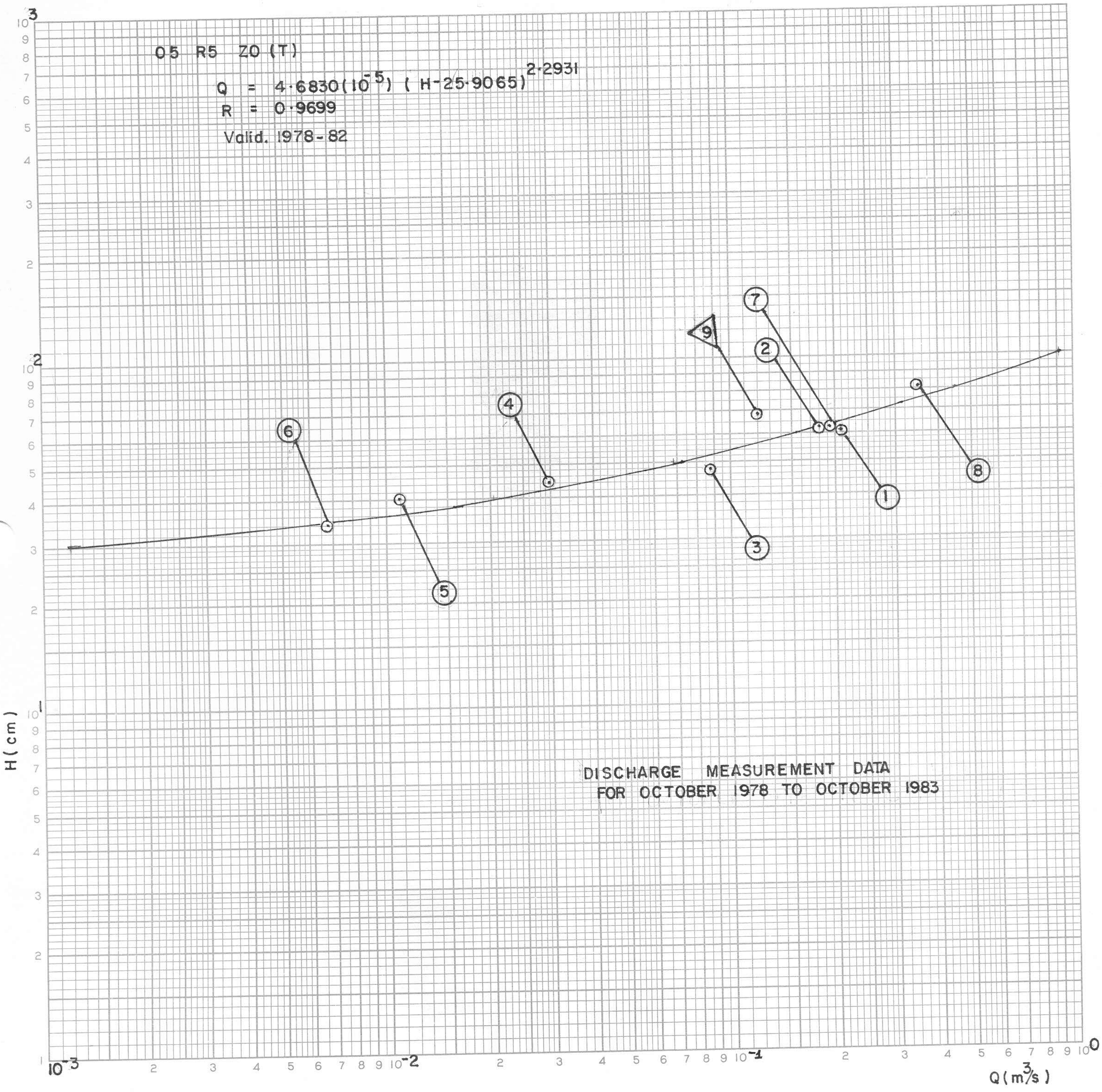


FIG. 2.19

06 R1 KA KAKATA ON DU RIVER

PERIOD OF OPERATION: 1977-till now

There are 13 flow measurement points as per reference 2. The measurement of 11 Nov. '79 was only recently found in the LHS archive, and could not have appeared in the above reference. This measurement becomes the 9th in terms of chronology; all subsequent measurements in reference 2 should therefore be shifted one unit down. Three additional measurements have been conducted by the LHS in recent times. These and the new D.M. No. 9 are as tabulated below:

NO.	DATE	H (cm)	Q (m^3/s)	A (m^2)	PERFORMED BY	REMARKS
9	Nov. 11, '79	133	9.50	13.83	LHS	
15	July 11, '83	88	8.90	11.30	"	
16	Sept.15, '83	333	43.50	74.30	"	
17	Oct. 20, '83	158	15.24	23.29	"	

It was noted that the points were scattered about 2 main curves on full logarithmic paper. Rating equation Q1 was derived using points from June '78 to Nov. '79. Point Nos. 8 and 9 were omitted in the derivation as they proved to be wrong.

RATING EQUATION I: $Q1 = 5.1486(10)^{-2}(H - 49.5542)^{1.3912}$
COEFFICIENT OF CORRELATION: R = 0.9739
RANGE OF STAGE: $65cm \leq H \leq 285cm$
PERIOD OF VALIDITY: JUNE,'78 to NOV. '79

Reconstruction of the highway bridge (1980-81) resulted in the gauge being temporarily transferred downstream of the old site. Flow measurement points obtained after re-installation of the gauge on the new bridge show a significant change in the parameter B, as appears in rating equation Q2 which was derived based on point numbers 10 to 17, all of which were used in the derivation. It is noted that these numbers refer to the new order of numbering introduced in paragraph 1 above.

RATING EQUATION II: $Q2 = 6.2308(10^{-2})\ (H - 24.5340)^{1.1398}$

COEFFICIENT OF CORRELATION: R = 0.9875

RANGE OF STAGE: $45cm \leq H \leq 333cm$

PERIOD OF VALIDITY: Dec. 1981 to Oct. 1983

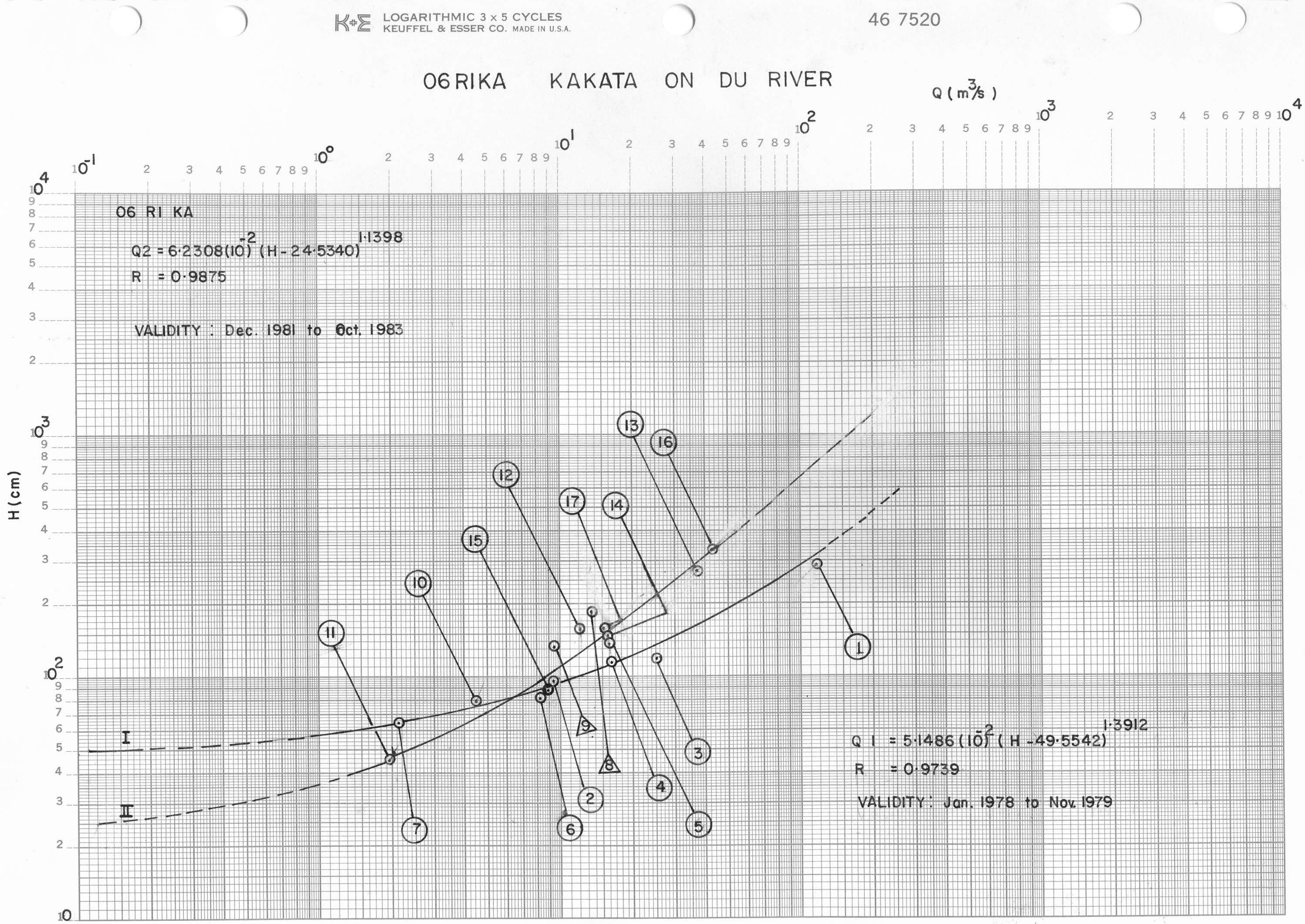

K+E LOGARITHMIC 3 x 5 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 7520
06 RIKA KAKATA ON DU RIVER
Q (m³/s)
H (cm)
06 RI KA
Q2 = 6·2308(10)^-2 (H - 24·5340)^1·1398
R = 0·9875
VALIDITY : Dec. 1981 to Oct. 1983
Q I = 5·1486 (10)^-2 (H - 49·5542)^1·3912
R = 0·9739
VALIDITY : Jan. 1978 to Nov. 1979
I
II

FIG. 2. 20

06 R1 KA(T) **KAKATA ON WEAMA CREEK**

PERIOD OF OPERATION: 1977-till now

To date, there are 7 flow measurement points (Q,H). All measurements have been conducted by the LHS, and the data span the period from October, 1981 to November, 1983.

The plotted points reveal a wide convexity. As this situation was introduced by measurement point No. 5, that point was omitted thereby reducing the effective range of applicability of the derived rating equation. Point No. 3 was also omitted, this time, because it proved to be wrong.

RATING EQUATION: $Q = 2.7951\ (10^{-56})\ (H + 320.3249)^{20.4366}$

COEFFICIENT OF CORRELATION: $R = 0.9812$

RANGE OF STAGE: $192\text{cm} \leq H \leq 264\text{cm}$

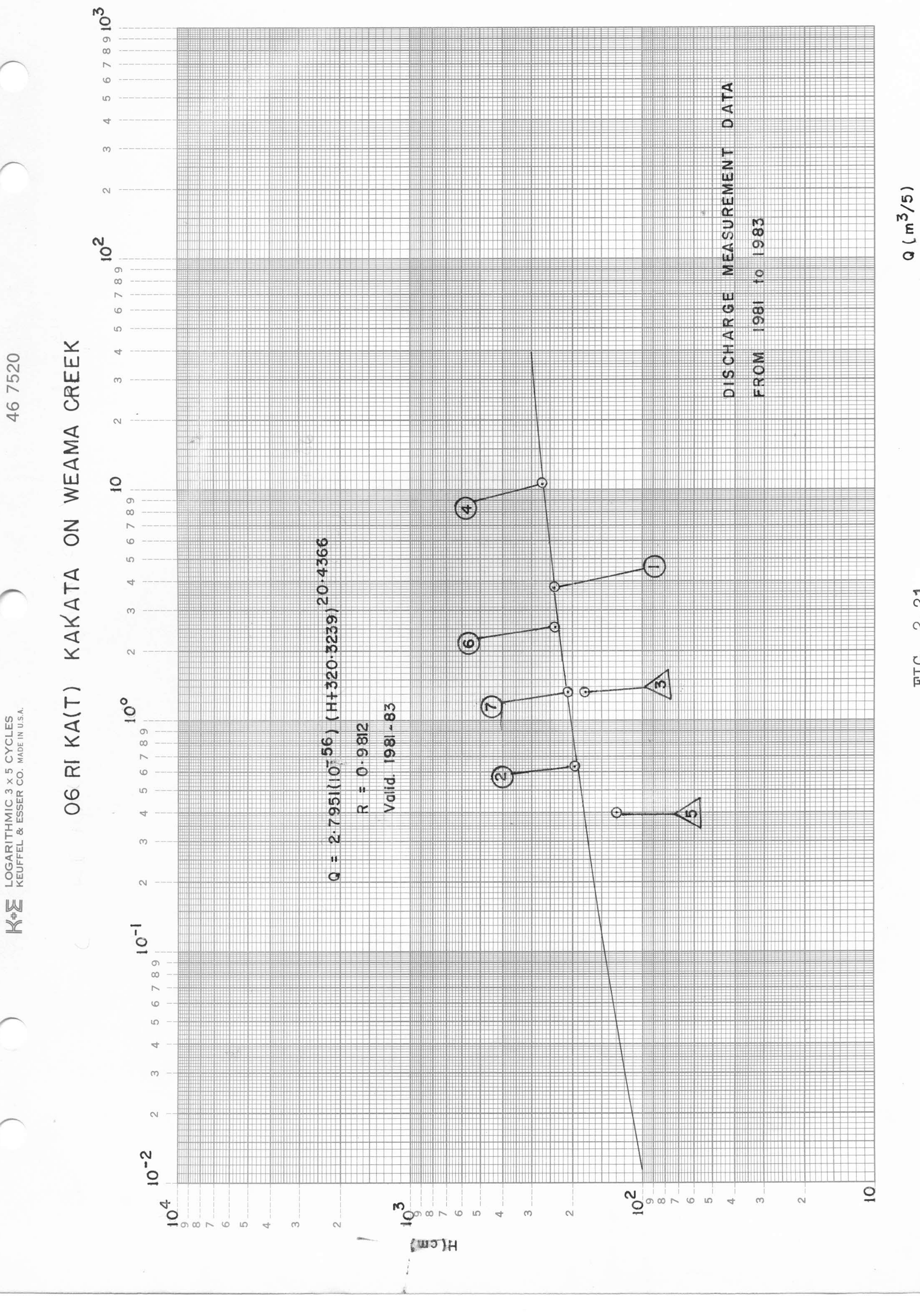

K+E LOGARITHMIC 3 x 5 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 7520
06 RI KA(T) KAKATA ON WEAMA CREEK
Q = 2·7951(10^-56)(H+320·3239)^20·4366
R = 0·9812
Valid. 1981-83
DISCHARGE MEASUREMENT DATA
FROM 1981 to 1983
Q (m3/5)
H(cm)

FIG. 2.21

06 R1 BN(T) BENTOL ON BENTOL (MANPAYE) CREEK

PERIOD OF OPERATION: 1975

Two measurements are recorded for this creek; as these were only recently discovered in the LHS Archives, they could not have been published in reference 2. Since both flows are unreferenced to a gauge height, neither the hydraulic approach nor the statistical method can be used to estimate a rating equation or curve. It is suggested that measurements be made in the future to facilitate rating this creek.

07 00 MF MOUNT FINLEY ON ST. JOHN

PERIOD OF OPERATION: 1957-1958

Since there are only three discharge measurements and two of them correspond to almost the same Gauge Height and taking in addition the unavailability of the D.M. notes, it is risky to derive the Rating Curve.

07 00 **FA** **FALLS ON ST. JOHN RIVER**

PERIOD OF OPERATION: 1958-till now

The Rating Curve was derived using the hydraulic approach with "BED PAR" PROGRAM on the base of two discharge measurements:

NO	DATE	GH (m)	Q (m^3/s)	A (m^2)	
				Acc. to DM note	Acc. to "BED PAR"
1	JUN.20, '78	4.11	235.33	414.5	414.5
2	APR.20, '78	3.67	140.52	414.7	371.4

For particulars, refer to "Rating Curves of Liberian Rivers, Part III: Hydraulic Estimation".

TABLE 2.4

07 00 FA

RATING TABLE

GH (m)	A x $RH^{2/3}$ ($m^{8/3}$)	Q (m^3/s)
4.11	1,055.93	201.79
4.10	1,051.84	201.01
4.00	1,011.29	193.26
3.90	971.35	185.63
3.80	932.02	178.11
3.70	893.32	170.71
3.60	855.24	163.44
3.50	817.81	156.28
3.40	781.01	149.25
3.30	744.87	142.34
3.20	709.40	135.57
3.10	674.59	128.91
3.00	641.34	122.56
2.90	608.98	116.38
2.80	577.29	110.32
2.70	546.27	104.39
2.60	515.93	98.59
2.50	486.29	92.93
2.40	457.34	87.40
2.30	429.10	82.00
2.20	401.57	76.74
2.10	374.77	71.62
2.00	348.71	66.64
1.90	323.40	61.80
1.80	301.44	57.60
1.70	281.36	53.76
1.60	262.04	50.07

GH (m)	A x $RH^{2/3}$ ($m^{8/3}$)	Q (m^3/s)
1.50	243.47	46.53
1.40	225.63	43.12
1.30	208.53	39.85
1.20	192.15	36.72
1.10	176.47	33.72
1.00	163.54	31.25
0.90	153.29	29.29
0.80	144.71	27.65
0.70	135.83	25.96
0.60	124.32	23.76
0.50	113.38	21.67
0.40	103.01	19.70
0.30	93.19	17.81
0.20	83.92	16.04
0.10	75.18	14.37
0.00	66.96	12.80

The values of A x $RH^{2/3}$ for lower GH than 0.00 are given in the table made by computer's printer, Ref. 3.

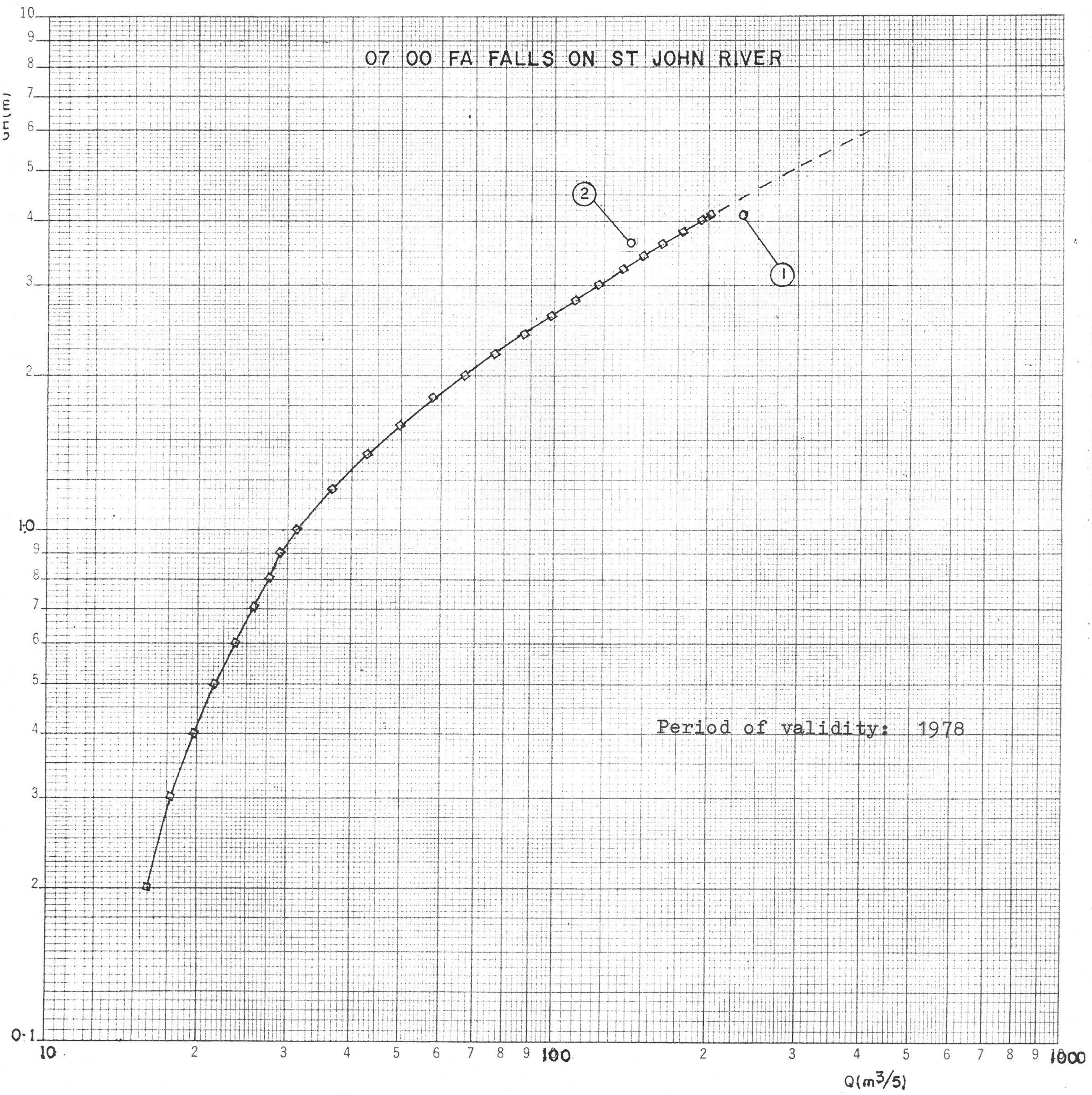

07 00 FA FALLS ON ST JOHN RIVER
GH(m)
10
9
8
7
6
5
4
3
2
1.0
0.1
2
1
10
2
3
4
5
6
7
8
9
100
1000
Q(m3/s)
Period of validity: 1978

FIG. 2.22

07 00 BA BAILA ON ST. JOHN RIVER

PERIOD OF OPERATION: 1958-till now

There are 31 flow measurements spanning the period from June, 1958 to April, 1979. The wire weight gauge which had been in use since 1958 was removed in 1979 for construction of a new bridge. It was reinstalled in 1982.

The flows have, in effect, been rated in two stages: the first curve (Q1) is applicable for the first 12 measurements all of which were conducted by SE.

RATING EQUATION I: $Q1 = 0.0898\,(H - 42.1092)^{1.5371}$

COEFFICIENT OF CORRELATION: $R = 0.9958$

RANGE OF STAGE: $70\text{cm} \leq H \leq 158\text{cm}$ Valid: 1958-1961

All subsequent measurements were conducted by the LHS. It is interesting how significantly parameter B has changed. To derive equation II, two points (30 and 31) were omitted from calculation.

RATING EQUATION II: $Q2 = 1.935\,(10)^{-25}\,(H + 190.5593)^{10.1051}$

COEFFICIENT OF CORRELATION: $R = 0.9753$

RANGE OF STAGE: $174\text{cm} \leq H \leq 305\text{cm}$ Valid: 1975-1978

07 00 BA BAILA ON ST. JOHN RIVER

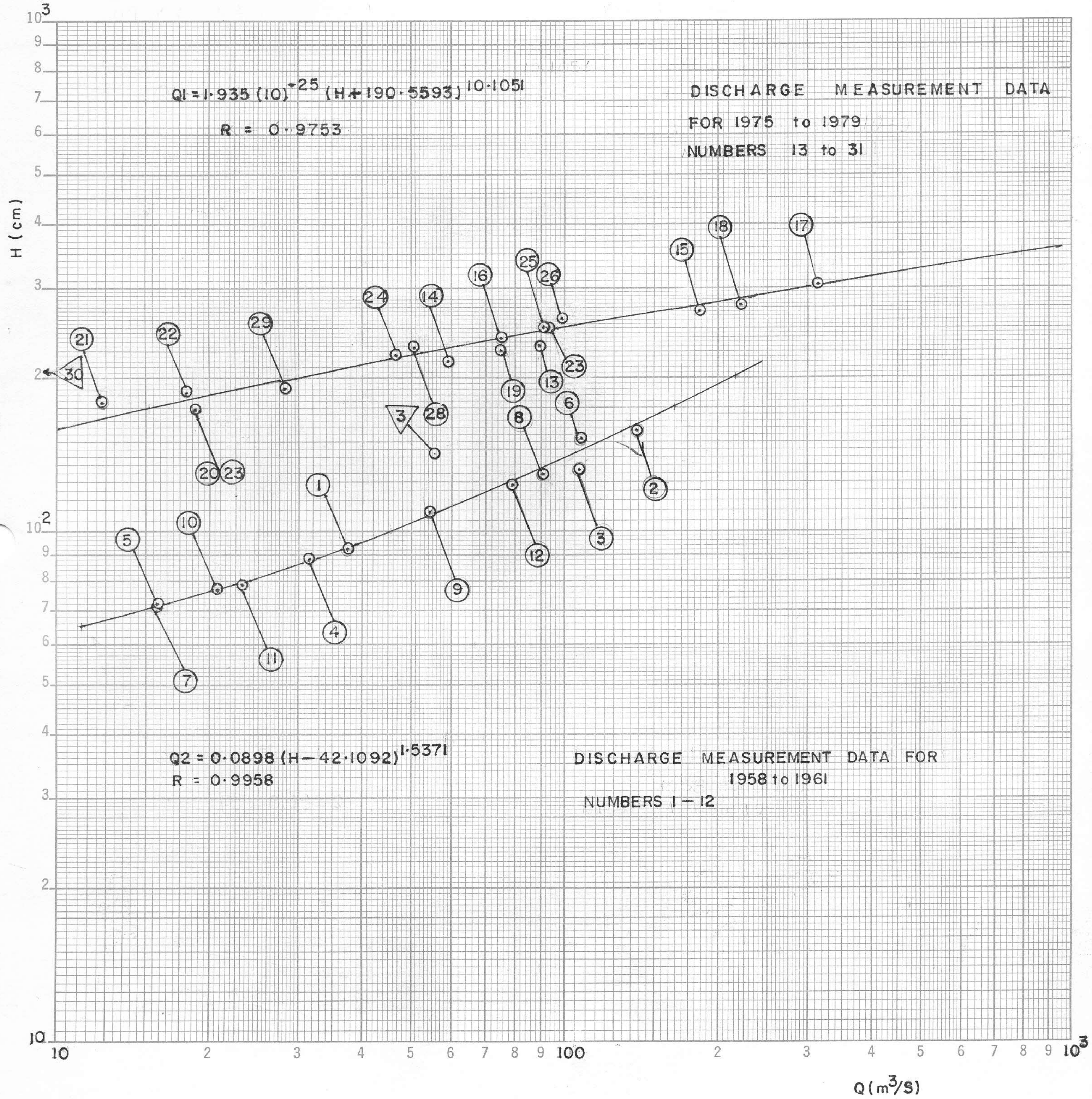


FIG. 2.23

07 R2 GB **GBANKA ON ZOR CREEK**

PERIOD OF OPERATION: 1973-till now

Out of the 24 discharge measurement points available, three were omitted (numbers 20 to 22), from computation of the parameters of the rating equation. Scrutiny of the rating curve will give some justification for this. Measurements span the period between February, 1973 and October, 1983. The first 13 of these measurements were conducted by the GWST; similarly number 15. All others were done by the LHS. Although the datum has reportedly changed, the magnitude of such change is not too great, as is suggested by parameter B. Furthermore, all points considered fall on a single curve.

RATING EQUATION: $Q = 1.6788\ (10^{-3})\ (H - 29.5993)^{1.8414}$

CORRELATION OF COEFFICIENT: $R = 0.9949$

RANGE OF STAGE: $39\text{cm} \leq H \leq 129\text{cm}$

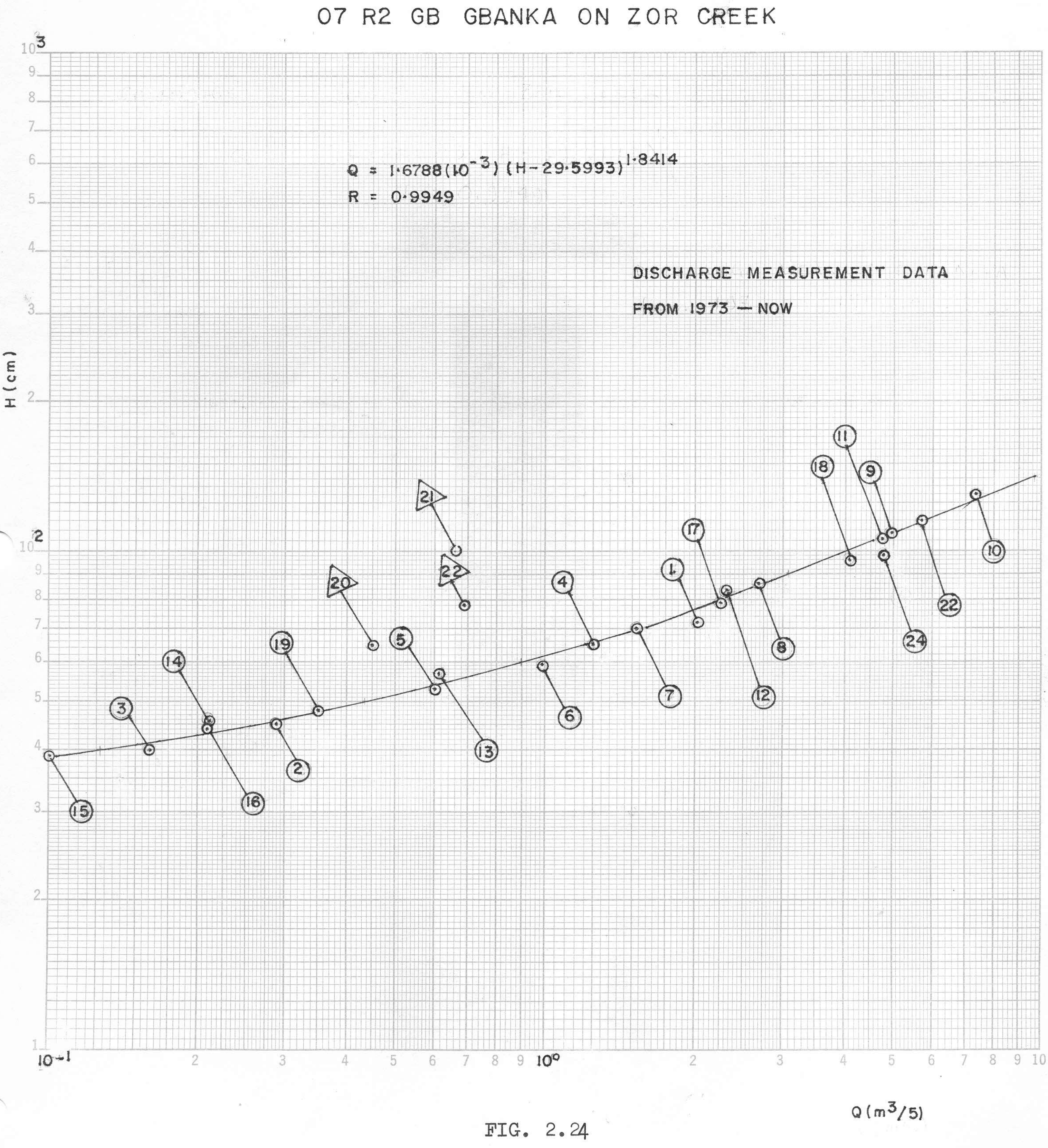

07 R2 GB GBANKA ON ZOR CREEK
Q = 1·6788(10^-3)(H-29·5993)^1·8414
R = 0·9949
DISCHARGE MEASUREMENT DATA
FROM 1973 — NOW
H (cm)
Q (m3/5)
10-1
10°
Logarithmic, 2 x 2 Cycles

FIG. 2.24

07 R2 CU(T) CUTTINGTON ON WUE CREEK

PERIOD OF OPERATION: 1974

Only one recorded measurement is available. Therefore the hydraulic method was used to derive the rating curve.

NO	DATE	GAUGE HEIGHT GH (m)	DISCHARGE $Q(m^3/s)$	AREA $A(m^2)$
1	OCT. 2, '74	3.26	13.47	40.74

For particulars, refer to "Rating Curve of Liberian Rivers, Part III: Hydraulic Estimation".

TABLE 2.5 RATING TABLE

07 R2 CU(T) CUTTINGTON ON WUE CREEK

H (m)	A x $(RH)^{2/3}$	Q (m3/s)
3.26	61.5894	13.47
3.20	59.4055	12.99
3.10	55.8169	12.21
3.00	52.2945	11.44
2.90	48.8408	10.68
2.80	45.4588	9.942
2.70	42.1514	9.219
2.60	38.9218	8.512
2.50	35.7735	7.824
2.40	32.7100	7.154
2.30	29.7354	6.503
2.20	26.8539	5.873
2.10	24.2557	5.305
2.00	21.7979	4.767
1.90	19.4608	4.256
1.80	17.1795	3.757
1.70	14.9719	3.275

H (m)	A x $(RH)^{2/3}$	Q (m3/s)
1.60	12.8836	2.818
1.50	10.9186	2.388
1.40	9.0819	1.986
1.30	7.3790	1.614
1.20	5.8398	1.277
1.10	4.4767	0.9791
1.00	3.2982	0.7213
0.90	2.2944	0.5018
0.80	1.4635	0.3201
0.70	1.2786	0.2796
0.60	0.9499	0.2077
0.50	0.7372	0.1612
0.40	0.4844	0.1059
0.30	0.2880	0.0630
0.20	0.1437	0.0314
0.10	0.0511	0.0112
0.00	0.0064	0.0014

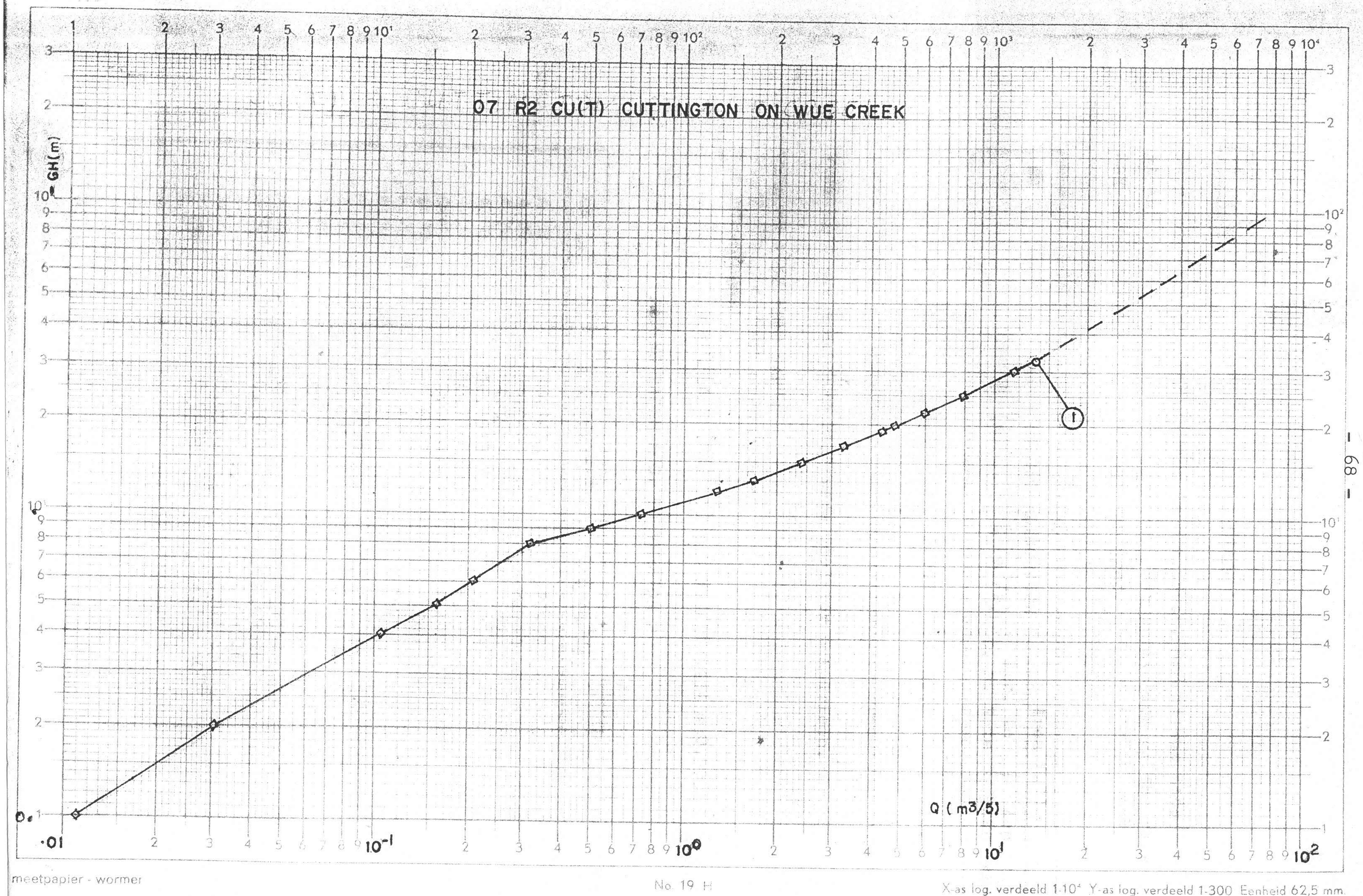

07 R2 CU(T) CUTTINGTON ON WUE CREEK
GH(m)
Q (m3/S)
.01
10^{-1}
10^{0}
10^{1}
10^{2}
0.1
1
meetpapier - wormer
No. 19 H
X-as log. verdeeld 1:10⁴ Y-as log. verdeeld 1-300 Eenheid 62,5 mm.

FIG. 2.25

07 L3 SC(T) **SACLAPEA ON WEH CREEK**

PERIOD OF OPERATION: 1980-till now

On the basis of all eight pairs of (H,Q) data (Ref. 1 p.53) the rating equation was derived by means of the "RAT CUR" PROGRAM. It has the form:

$$Q = 0.0473\ (H-44.3189)^{0.9155}$$

COEFFICIENT OF CORRELATION: $R = 0.9898$

RANGE OF STAGE: $50 \leq H\ (cm) \leq 157$

All measurements were made in the period, Dec. 4, 1980 to July 8, 1982.

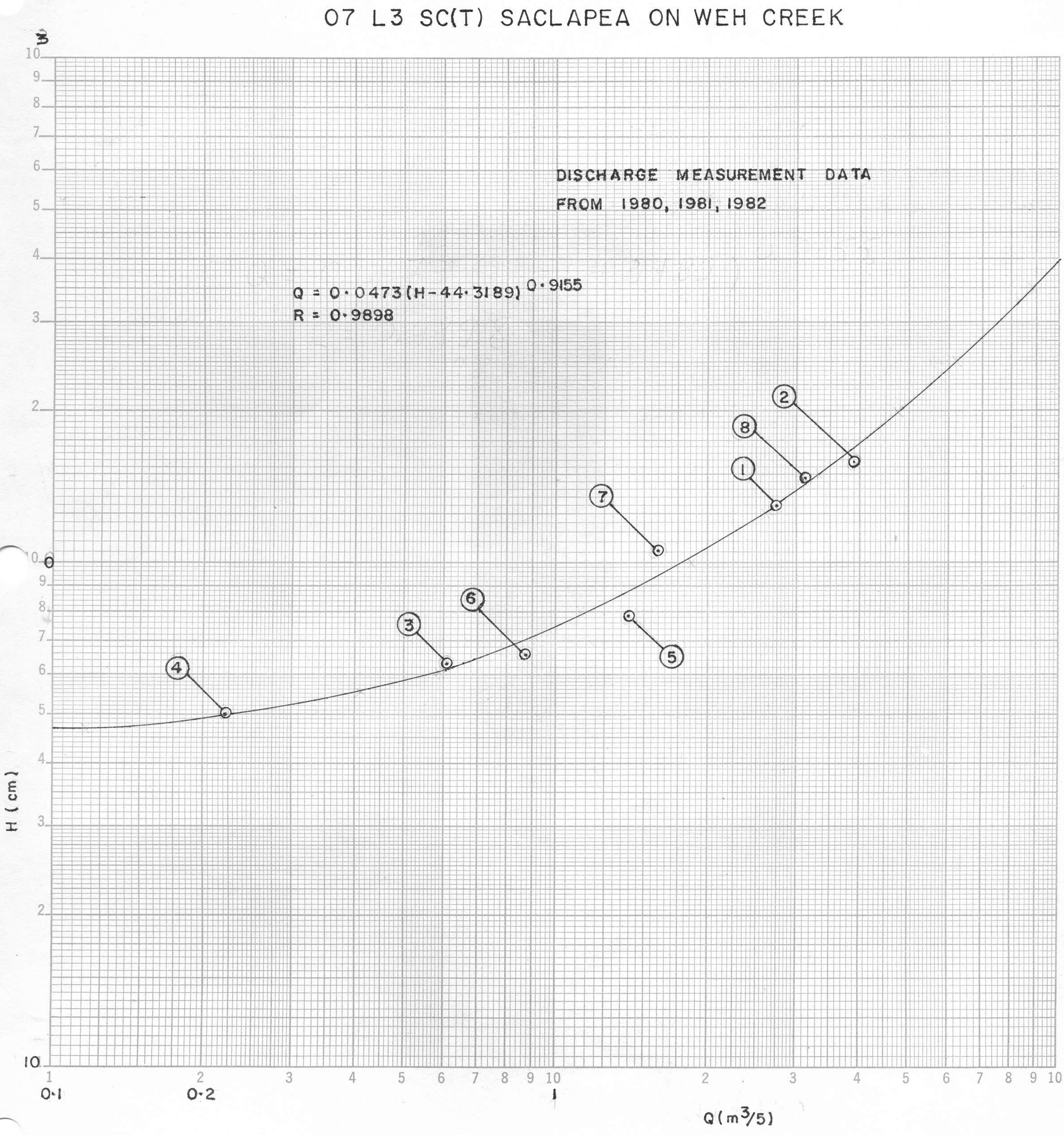


FIG. 2.26

Logarithmic, 2 x 2 Cycles

07 L3 SN(T) SANNIQUELLE ON BLEE CREEK

PERIOD OF OPERATION: 1973-till now

Discharge measurement data are available for 1973 (12 measurements), 1974 (3 measurements) and 1981 (1 measurement). One rating curve was fitted to these data. It was derived by means of "RAT CUR" PROGRAM.

RATING EQUATION: $Q = 4.4967E{-8}\ (H - 30.3708)^{3.8986}$

COEFFICIENT OF CORRELATION: $R = 0.9902$

The water level interval of discharge measurements, i.e.

RANGE OF STAGE: $67 \leq H\ (cm) \leq 151$

Measurements made in the period: Feb. 6, 1973 - Nov. 20, 1981

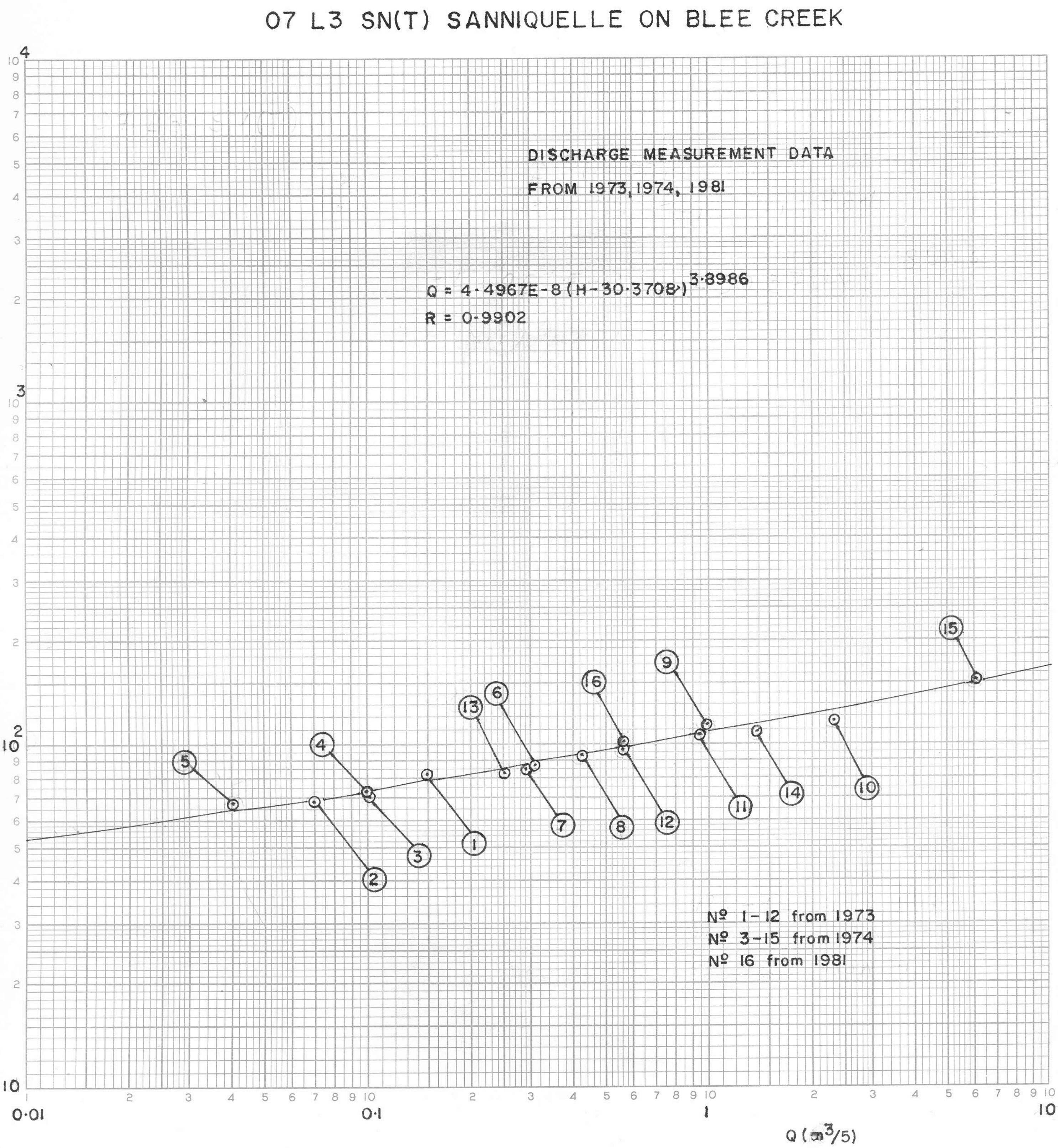

07 L3 SN(T) SANNIQUELLE ON BLEE CREEK
DISCHARGE MEASUREMENT DATA
FROM 1973, 1974, 1981
Q = 4·4967E-8 (H-30·3708)^3·8986
R = 0·9902
Nº 1-12 from 1973
Nº 3-15 from 1974
Nº 16 from 1981
H (cm)
Q (m³/s)
0·01
0·1
1
10

FIG. 2.27

10 R3 TA TAPETA ON GWEHN CREEK

PERIOD OF OPERATION: 1978-till now

There are seven flow measurement points (Q,H) recorded for this gauging station. The points span the period from Mar. 1981 to Oct. 1983. All available points were utilized in deriving the rating equation. All flow measurements have been conducted from the cross-section at the staff gauge. Datum has remained unchanged since the installation was made in 1981.

RATING EQUATION: $Q = 6.4779\ (10^{-3})\ (H - 54.8371)^{1.0756}$

COEFFICIENT OF CORRELATION: $R = 0.9624$

RANGE OF STAGE: $59\text{cm} \leq H \leq 116\text{cm}$

Additional D.M. - data

NO.	DATE	H (cm)	Q (m^3/s)	A (m^2)	PERFORMED BY	REMARKS
6	June 26, '83	94	0.254	2.9	LHS	
7	OCT. 5, '83	93	0.450	2.08	LHS	

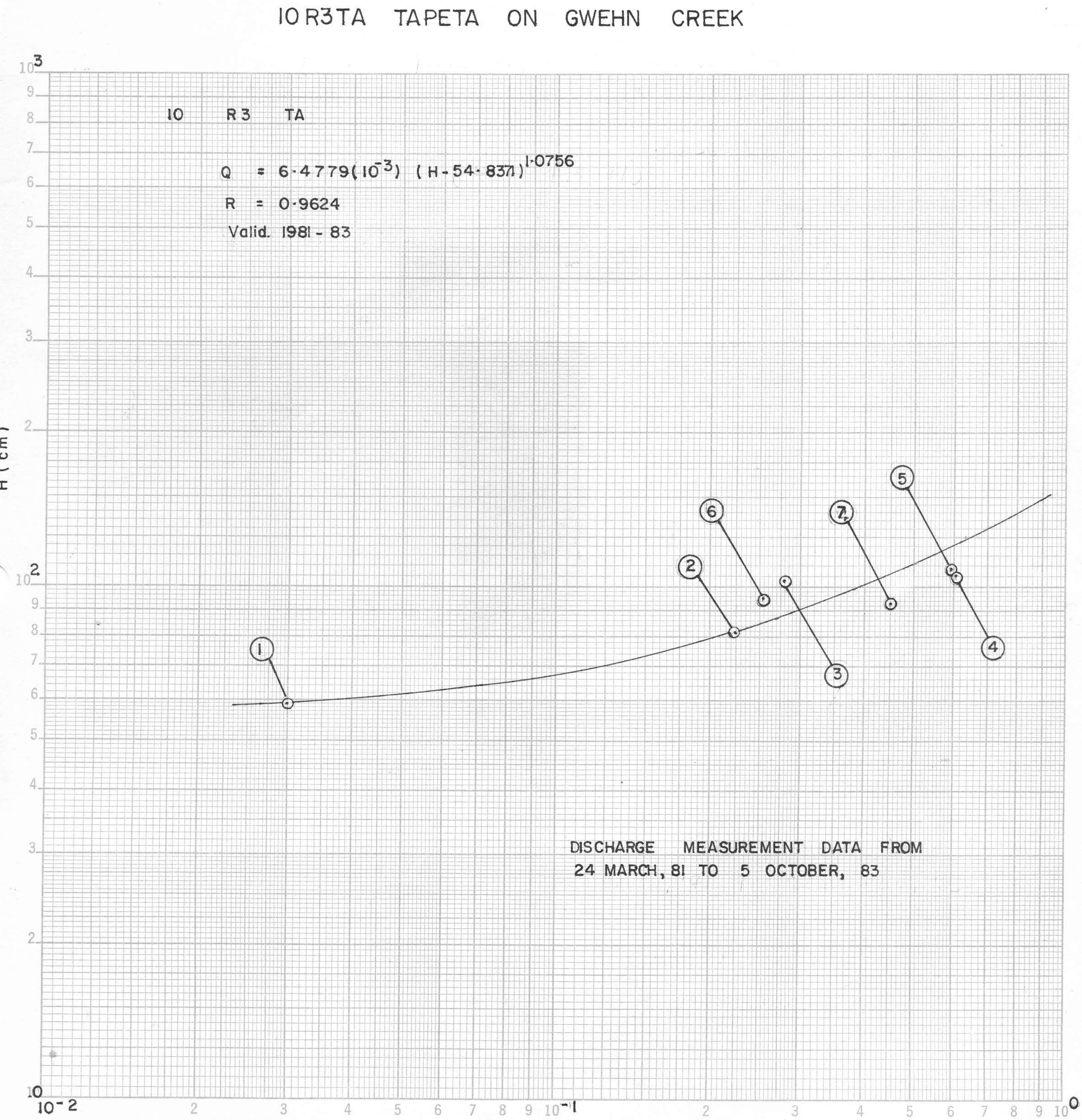

10R3TA TAPETA ON GWEHN CREEK
10 R3 TA
Q = 6·4779(10⁻³) (H-54·8371)^1·0756
R = 0·9624
Valid. 1981 - 83
H (cm)
DISCHARGE MEASUREMENT DATA FROM
24 MARCH, 81 TO 5 OCTOBER, 83
1
2
3
4
5
6
7
Q (m³/s)

FIG. 2.28

18 R2 BL BOLULU ON BOLULU CREEK

PERIOD OF OPERATION: 1982-till now

Only one recorded measurement is available. The rating curve for gauge heights which are less than or equal to 4.88m was derived using the hydraulic method.

NO	DATE	GAUGE HEIGHT GH (m)	DISCHARGE Q (m^3/s)	AREA A (m^2)
1	NOV. 12, '82	4.88	2.997	16.70

The computation as well as the input - output data are given in the Rating Curve of Liberian Rivers, Part III: Hydraulic Estimation". Therefore only the final result i.e. the rating curve according to Version II of "BED PAR" is shown here.

TABLE 2.6 SKELETON RATING TABLE

GH (m)	Q (m^3/s)	GH (m)	Q (m^3/s)
4.88	2.997	4.00	0.6588
4.80	2.712	3.90	0.5020
4.70	2.376	3.80	0.3660
4.60	2.063	3.70	0.2515
4.50	1.771	3.60	0.1608
4.40	1.502	3.50	0.0949
4.30	1.257	3.40	0.0466
4.20	1.033	3.30	0.0146
4.10	0.8360	3.20	3.9×10^{-4}

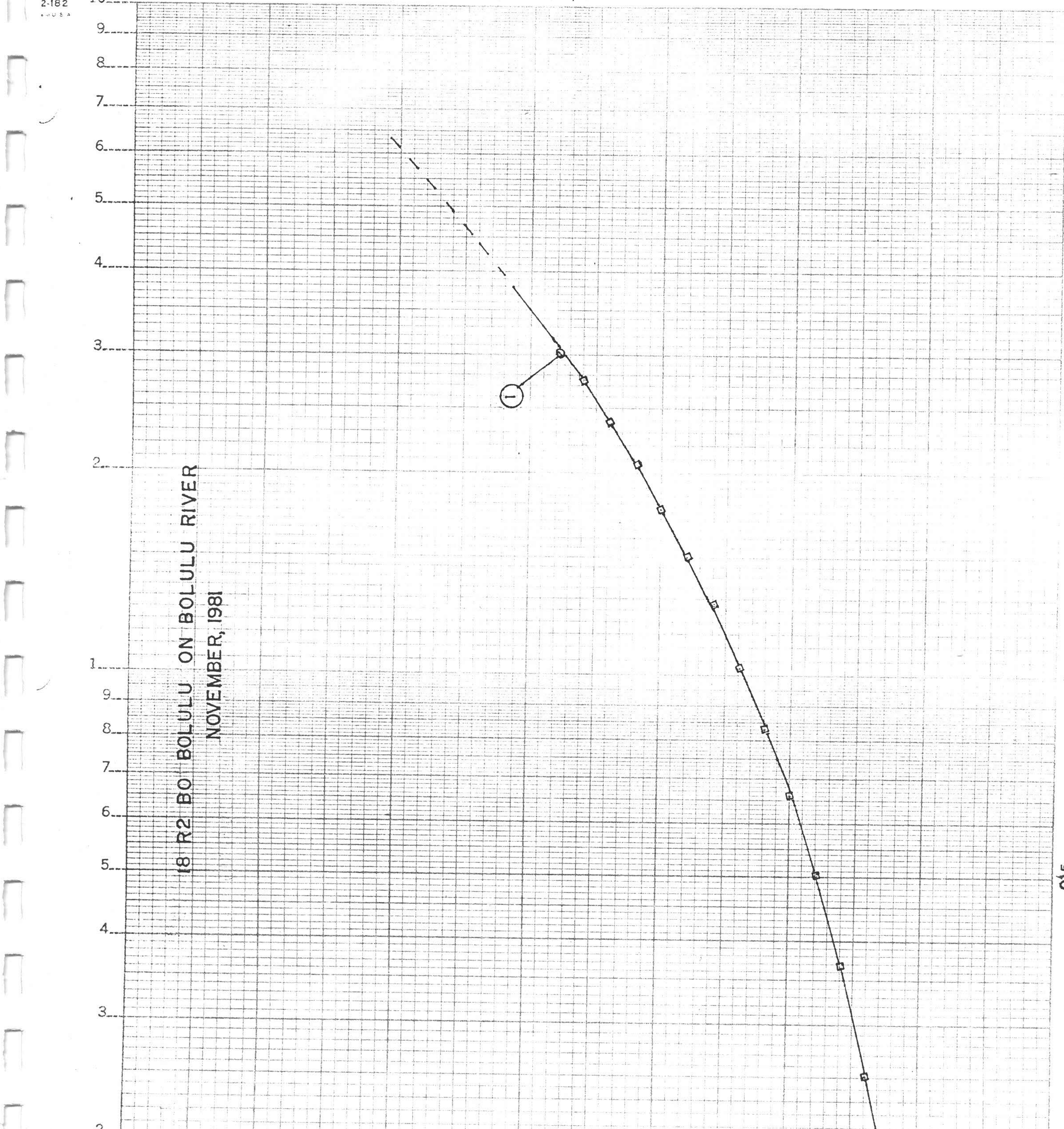

18 R2 B0 BOLULU ON BOLULU RIVER
NOVEMBER, 1981
Q(m3/5)
GH(m)
5.0
4.5
4.0
3.5
3.0
0.1
0.5
1
2
3
10
emi-Logarithmic
cles x 10 to the inch

FIG. 2.29

19 R4 ZW ZWEDRU ON DOUBE RIVER

PERIOD OF OPERATION: 1973-till now

There are 27 flow measurements recorded for this station. All measurements were conducted from the cross-section at the highway bridge. The gauge height (cm) from the staff gauge at this site must be added to 85cm.

Measurement number 19 of 22nd December, 1976 is not referenced to a gauge height. Measurement numbers 19 through 22 were found to lie far away from the others and as such were omitted when the computer program "RAT CUR" was used to get the rating equation. Data utilized were those accumulated between March, 1973 and June, 1983.

RATING EQUATION: $Q = 8.3028\ (10^{-3})\ (H - 72.3949)^{1.5557}$

COEFFICIENT OF CORRELATION: $R = 0.9858$

RANGE OF STAGE: $68\text{cm} \leq H \leq 365\text{cm}$

Additional D.M. - data

NO.	DATE	H (cm)	Q (m^3/s)	A (m^2)	PERFORMED BY	REMARKS
27	June 25, '83	251	27.86	63.1	LHS	

19 R4 ZW ZWEDRU ON DOUBE RIVER

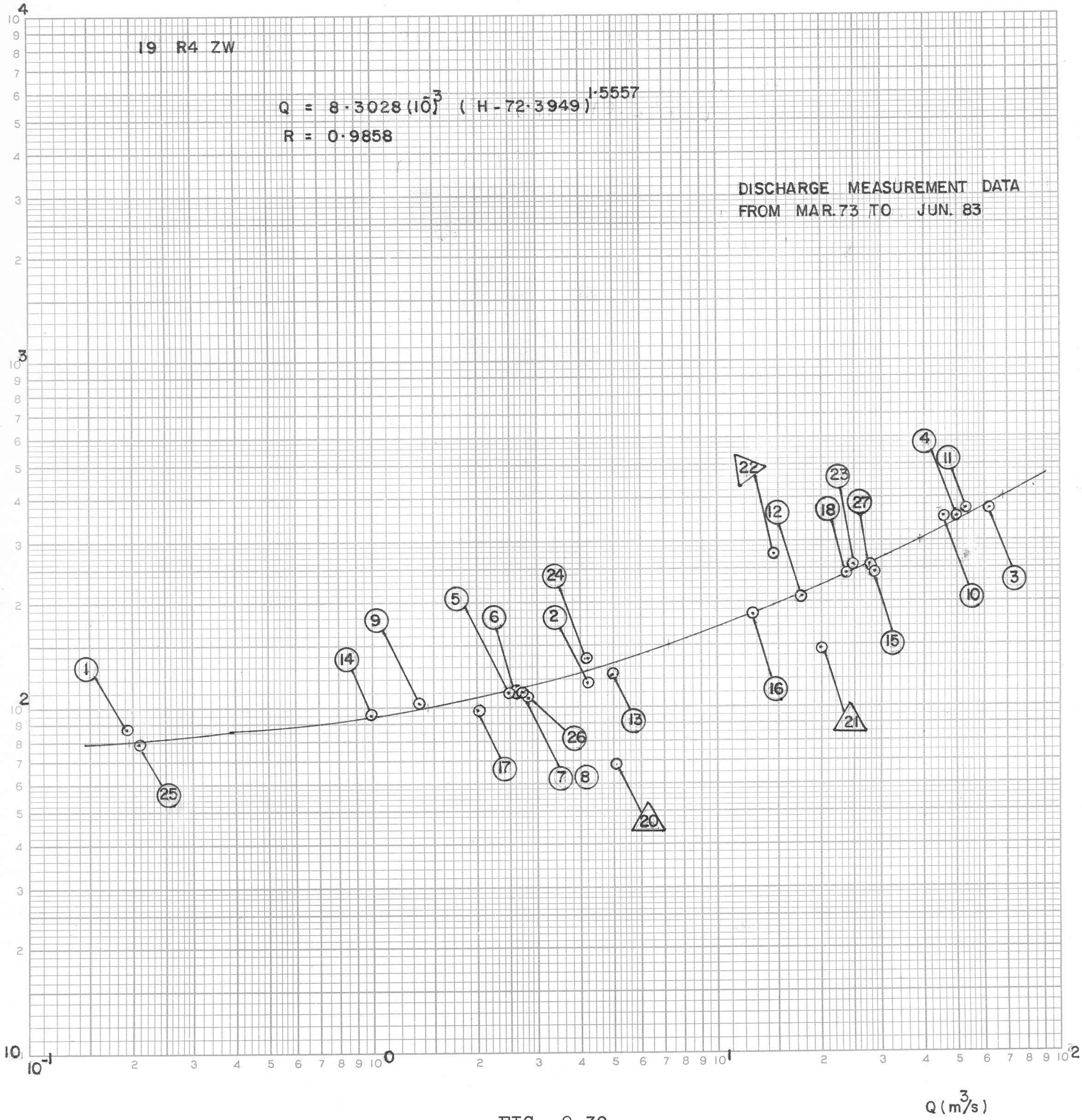


FIG. 2.30

3. COMPREHENSIVE REVIEW OF RESULTS

Results from all rating processes were the subject of a comprehensive review aimed at revealing erroneous or low accuracy results. The review was based on the statistical as well as on physical approach.

3.1 TEST OF SIGNIFICANCE FOR CORRELATION COEFFICIENT

Errors of various origins can cause correlation of (Q,H) - - pairs at some stations to be non-significant. To check it, a one sided test of significance was conducted on the correlation coefficients from each rating process. The level of significance (alpha) was fixed at 1%. Clearly the null hypothesis is one hypothesis with no correlation between each set of data points, (H_i, Q_i; i = 1,2,...,n). Alpha should be interpreted as being the probability of rejecting the null hypothesis if that hypothesis is true. Table 3.1 shows critical values (Rc) of coefficients of correlation for each appropriate sample size. It can be seen that the tests conducted failed to reject the null hypothesis. Values of Rc should therefore be interpreted as the minimum permissible values of correlation coefficients which can be rationally accepted for the given sample size.

TABLE 3.1 COMPREHENSIVE REVIEW OF RESULTS

CODE	NAME OF STATION	NAME OF RIVER	R	SAMPLE SIZE	Rc	N	PERIOD OF VALIDITY
01 00 KN	KONGO	MANO	0.9942 0.9973	29 5	0.4640 0.9172	2.3380 0.8850	1958-1980,1982 1981
01 00 JE	JENNIE	MANO	0.9835	23	0.5168	1.0046	1976-now
01 00 BH	BOLAHUN	ZELIBA	0.9952	6	0.8745	0.7696	1958-1973
01 00 KL	KOLANUM	KAIHA	-		-		1982-now
01 00 JT	JOHNNY TOWN	ZELIBA	0.9988 0.9976	6 9	0.8745 0.7646	0.80686 1.9147	1970 1973-1974
01 00 VO	VOINJAMA	ZELIBA	0.9581	16	0.6055	2.1277	1973-1981
01 00 BO(T)	BOLAHUN	WAWO CREEK	0.9931 0.9931	3 9	0.9900 0.7646	1.4928 1,4928	1958-1961 1982-1983
01 L3 WO(T)	WOLOGIZI	MASSOH CREEK	0.9761	5	0.9172	3.1179	1978-1979
02 01 BE	BENDUMA	MAFFA	HA	3	-		1983 (Dec.)
02 05 RO	ROBERTS-PORT	FASA CREEK	0.9982	10	0.7348	5.2234	1974-1980
03 00 DU	DUOGOMAI	LOFA	0.9988	12	0.6835	1.8086	1970-1982
03 L3 LU	LUYEAMA	LAWA	0.9676	14	0.6411	1.7666	1970-1983
05 00 MC	MT. COFFEE	ST.PAUL	0.9892	14	0.6411	2.4212	1958-1966
05 00 HE	HEINDI	ST.PAUL	HA	3	-		1980-1981
05 00 WB	WALKER BRIDGE	ST.PAUL	0.9812	21	0.5368	1.8007	1958-1981
05 00 MC(T)	MT. COFFEE	QUAIN (KOIN)CR.	-	1	-		1980-now
05 R3 BY	BELLE YAL-LA	TUMA CREEK	0.9972	9	0.7646	1.3666	1967-1968
05 R3 PA	PALAKALE	TUMA CREEK	0.9978	13	0.6614	1.4412	1967-1968
05 R4 GB	GBAKWELLIE	VAI	0.9961	18	0.5751	1.1634	1967-1968
05 R5 ZO(T)	ZORZOR	BAMAYEA CREEK	0.9699	8	0.7977	2.2931	1978-1983
06 R1 KA	KAKATA	DU	0.9739 0.9875	7 8	0.8343 0.7977	1.3912 1.1398	1978-1979 1981-1983
06 R1 KA(T)	KAKATA	WEAMA CREEK	0.9812	5	0.9172	20.4366	1981-1983
06 R1 BN(T)	BENTOL	BENTOL CREEK	-	2	-	-	1975

TABLE 3.1 (cont'd)

CODE	NAME OF STATION	NAME OF RIVER	R	SAMPLE SIZE	Rc	N	PERIOD OF VALIDITY
07 00 MF	MT. FINLEY	ST. JOHN	-	3	-	-	1957-1958
07 00 FA	FALLS	ST. JOHN	HA	2	-	-	1978
07 00 BA	BAILA	ST. JOHN	0.9958 0.9753	12 17	0.6835 0.5897	1.5371 10.1051	1958-1961 1973-1979
07 00 GB	GBANKA	ZOR CREEK	0.9949	21	0.5368	1.8414	1973-1983
07 R2 CU(T)	CUTTINGTON	WUE CREEK	HA	1			1974
07 L3 SC(T)	SACLAPEA	WEH CREEK	0.9898	8	0.7977	0.9155	1980-1982
07 L3 SN(T)	SANNIQUE-LLIE	BLEE CREEK	0.9902	12	0.6835	3.8986	1973-1981
10 R3 TA	TAPETA	GWEHN CREEK	0.9624	7	0.8343	1.0756	1981-1983
18 R2 BL	BOLULU	BOLULU CREEK	HA	1			1982
19 R4 ZW	ZWEDRU	DOUBE	0.9858	23	0.5168	1.5557	1973-1983

LEGEND:

HA... Hydraulic Approach was used for flow rating.

- ... Rating curve has not been derived due data insufficiency.

N ... Exponent in rating equation.

Rc... Critical value for coefficient of correlation (R) at a significance level of 1% (alpha = 0.01).

3.2 PHYSICAL VERIFICATION OF THE N - PARAMETER

On Table 3.1 it is seen that parameter N varies in a wide interval ($0.77 \leq N \leq 20.44$) with 3 of the 29 values bigger than 5, and 4 of the 29 values lower than 1.

The question arises whether such variation is consistent with the physics of the flow regime. What range of variability is appropriate for N ?

To answer these questions a slope - roughness parameter D was defined as sqrt (So/n^2) where So is the water surface slope and n is Manning's roughness coefficient. From the basic expression of the rating equation, it is apparent that our task is to represent Manning's hydraulic equation in the following form:

$$Q = Cy^N \qquad (3.1)$$

where Q is the discharge;

y is the depth of flow such that $y = H + B$;

H is the gauge height and B is the depth at the active part of the gauging cross-section which corresponds to zero gauge height;

C is the coefficient;

N is the hydraulic exponent.

With these definitions it can be shown that N is physically dependent on channel geometry, depth (y) and the slope - roughness factor (D) by the equation:

$$N = \frac{y}{3A} \cdot \left(5T - 2R\frac{dP}{dy}\right) + \frac{1}{D} \cdot \frac{dD}{dy} \qquad (3.2)$$

where A - area of flow measurement cross section,

T - top width of the section,

R - hydraulic radius,

P - wetted perimeter,

y - depth of flow;

all quantities in consistent units.

Assuming the D - factor to be independent of depth (y), i.e. $dD/dy = 0$ gives $N = \frac{y}{3A} (5T - 2R \frac{dP}{dy})$ (3.3)

It is therefore possible to derive N as a function of depth for every cross section on the base of depth - distance diagram only. To do it for natural shapes of river channel the procedure should be computerized using a suitable finite difference scheme.

It can be recalled that in Ref. 1 the authors underscored the basic conditions under which a statistically derived rating equation would tend to approximate the true hydraulic relationship. Where these conditions are met and the D - factor can be assumed as being constant, the procedure just outlined can be used to estimate the statistical parameter N that one can expect for natural channel cross-sections.

In cases when D varies significantly with depth, the Equation 3.2 must be applied. Having several numbers of discharge measurements corresponding to various gauge heights, the slope - roughness factor D can be computed for every discharge measurement as

$$D = \frac{Q}{A*R^{2/3}} \qquad (3.4)$$

where the conveyance ($AxR^{2/3}$) is estimated by "BED PAR" Computer Program (Ref. 3). The relationship of D versus y can then be estimated, and be consequently used to derive the slope - friction term of Eq. 3.2; such exercise may comprise the scope of a seperate study.

An attempt has been made, however, to give physical significance to the hydraulic exponents for Liberian river gauging cross-sections by assuming invariance of the slope - roughness parameter with depth of flow. To achieve this objective, elementary sections were scrutinized as appears in Fig. 3.1. Accordingly,

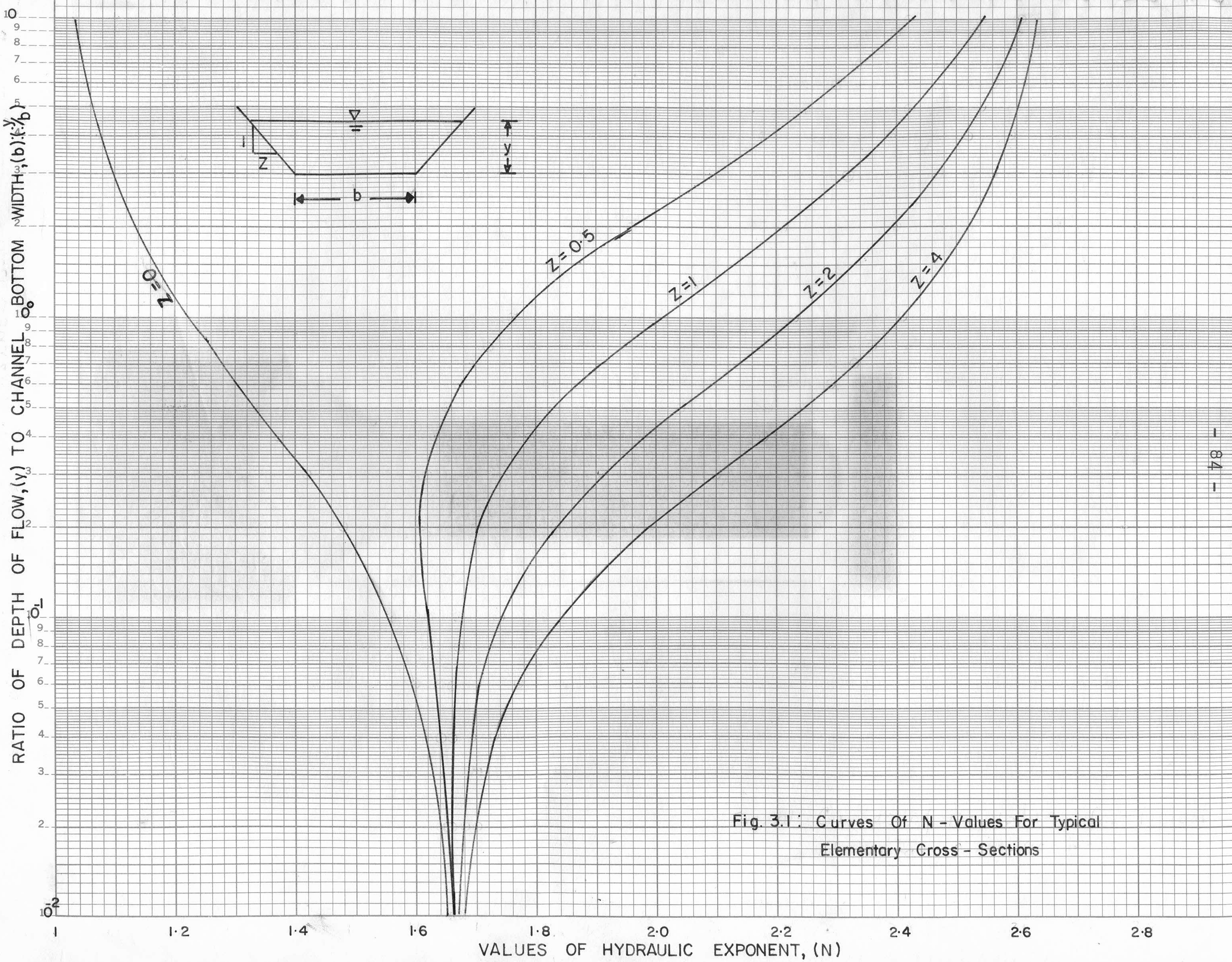


Fig. 3.1: Curves Of N - Values For Typical Elementary Cross - Sections

quasi - rectangular cross-sections will give values of hydraulic exponent such that

$$1.000 \leq N \leq 1.666,$$

while for quasi - trapezoidal sections, the value of N will vary within the range:

$$1.6666 < N \leq 2.666.$$

Considering a natural river channel for which $z \geq 0$ (Fig. 3.1), N = 1 is the lower bound for the variation of parameter N. However from statistical computation, it was observed that in 4 of 29 cases, N attained a value less than unity. Since one can not be sure whether the necessary and sufficient conditions for approximating the physical rating curve by logarithmic regression were fulfilled, it can be assumed that the physical parameter N should be associated with the probability defined by the sample size within the interval defined by two regression coefficients, i.e. ln Q versus ln (H - B) and vice versa; that is

$$N \leq N_{ph} \leq N/R^2 \qquad (3.5)$$

where N - statistical estimate of N obtained from the regression of ln Q versus ln (H - B),

N_{ph} - physical value of N, and

R - coefficient of correlation.

Results displayed in Table 3.2 show the upper limit of parameter N lower than 1.0 for each of four rating curves. These rating curves should therefore be considered with reservation and suspicion. Since for the Kongo and Saclapea Hydrological stations the same flow conditions as used in calculation may still exist, it is recommended to conduct more discharge measurements and to recalculate the rating curves.

TABLE 3.2 INTERVAL OF VARIABILITY FOR THE N - PARAMETER

CODE	NAME OF		SAMPLE	R	LIMITS		PERIOD OF
	STATION	RIVER	SIZE		LOWER N	UPPER N/R^2	VALIDITY
01 00 KN	KONGO	MANO	5	0.9973	0.8850	0.8898	1981

TABLE 3.2 (cont'd)

CODE	NAME OF		SAMPLE	R	LIMITS		PERIOD
	STATION	RIVER	SIZE		LOWER N	UPPER N/R^2	OF VALIDITY
01 00 BH	BOLAHUN	ZELIBA	6	0.9952	0.7696	0.7770	1958-73
01 00 JT	JOHNNY TOWN	ZELIBA	6	0.9988	0.8069	0.8088	1970
07 L3 SC (T)	SACLAPEA	WEH CR.	8	0.9898	0.9155	0.9345	1980-82

A value of parameter N equal to 2.666(6) defines the upper limit for a trapezoidal section. However 5 cases (Table 3.3) of 29 show values of N higher than this. The question arises whether such high values can be physically justified.

TABLE 3.3 STATIONS WITH RATING EQUATIONS HAVING N BIGGER THAN 2.666

CODE	NAME OF		N	SAMPLE	R	PERIOD OF
	STATION	RIVER		SIZE		VALIDITY
01 L3 WO(T)	WOLOGIZI	MASSOH CR.	3.1179	5	0.9761	1978-79
02 05 RO	ROBERTS PORT	FASA CR.	5.2234	10	0.9982	1974-80
06 R1 KA(T)	KAKATA	WEAMA CR.	20.4366	5	0.9812	1981-83
07 00 BA	BAILA	ST. JOHN	10.1051	17	0.9753	1975-79
07 L3 SN(T)	SANNIQUELLIE	BLEE CR.	3.8986	12	0.9902	1973-81

To give possible physical reasons for values of parameter N tending to exceed 2.666(6) a complex channel geometry must be taken into consideration. Let's assume the channel consists of three rectangular segments as shown in Fig. 3.2. Applying Eq. 3.3 to this case results in the following equation for the hydraulic exponent, N:

$$N = \frac{1}{3(a(b-1)+1)}\left(5b - \frac{4c(a(b-1)+1)}{a+2c}\right) \qquad (3.6)$$

where:

$$a = y_2/y > 0 \quad ; \quad b = T/B \geq 1 \quad ; \quad c = y_2/T > 0$$

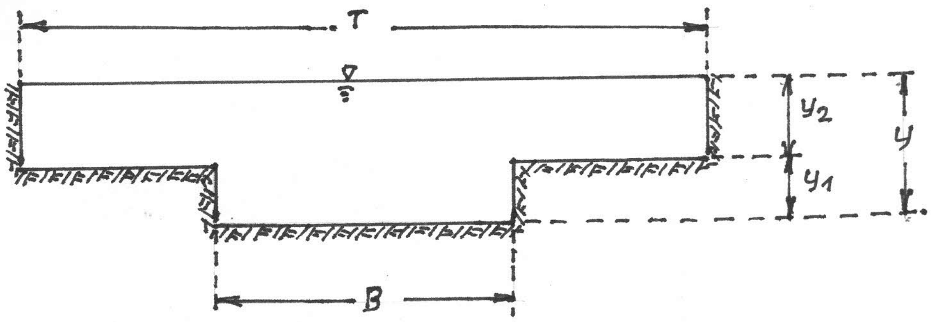


Fig. 3.2 Channel Section consisting of 3 Rectangular Segments

Comparing the range of N-values on Fig. 3.1 with those in Table 3.4, it is easy to guess that one can get much higher values for the physical exponent N than shown in Table 3.3 by taking the upper part of the channel to be trapezoidal rather than rectangular.

TABLE 3.4* VARIATION OF PARAMETER N WITH PARAMETERS OF FIG. 3.2

b \ a	10^{-3}	10^{-1}	2.0
1	1.000 ≤ N ≤ 1.666	1.000 ≤ N ≤ 1.666	1.000 ≤ N ≤ 1.666
2	2.663 ≤ N ≤ 3.330	2.389 ≤ N ≤ 3.056	1.333 ≤ N ≤ 2.000
3	4.323 ≤ N ≤ 4.990	3.564 ≤ N ≤ 4.231	1.476 ≤ N ≤ 2.143
5	7.633 ≤ N ≤ 8.300	5.444 ≤ N ≤ 6.111	1.606 ≤ N ≤ 2.273
10	15.851 ≤ N ≤16.518	8.500 ≤ N ≤ 9.167	1.714 ≤ N ≤ 2.381
15	23.989 ≤ N ≤24.655	10.333 ≤ N ≤11.000	1.753 ≤ N ≤ 2.415

Note:* The effective lower limit for 1/c was taken as zero while the upper limit was set at positive infinity.

Although the above analysis failed to contradict the possibility of high values of the physical exponent, N for complex geometries, it is not quite clear whether the case considered actually fits channel geometries at the hydrological stations listed in Table 3.3. Besides, the upper limit of parameter N for given values of parameters b and c correspond to the depth in the upper part of the channel tending to zero, i.e. $a \to 0^+$; while the statistical value of N roughly corresponds to the mean value within the interval of discharge measurements. Therefore, it is recommended to derive the physical exponent N as a function of gauge height for every cross-section listed in Table 3.3. This may be done by using information obtained from Discharge Measurement (D. M.) notes. In particular, this exercise should be undertaken with a view to determining whether the shape of the channel at Baila on St. John River changed to such extent as to give in 1958-1961, N = 1,5371; while in 1975-1979, N = 10,1031.

The hydraulic method was used to derive rating curves for 5 of 32 hydrological stations. The method was used due to the scarcity of D.M. - data at these stations. Concerned stations are listed in Table 3.5 with the corresponding values of slope - roughness factor. By collecting more information of such kind the basis for deriving rating curves in cases where D.M. - data are not available, will be established.

TABLE 3.5 STATIONS FOR WHICH THE HYDRAULIC APPROACH WAS USED

CODE	NAME OF		NO. OF	SLOPE - ROUGHNESS
	STATION	RIVER	D. M.	FACTOR, $D = \sqrt{So/n^2}$
02 01 BE	BENDUMA	MAFFA	3	0.4239
05 00 HE	HEINDI	ST. PAUL	3	0.3102
05 00 FA	FALLS	ST. JOHN	3	0.1911
07 R2 CU(T)	CUTTINGTON	WUE CR.	1	0.2187
18 R2 BL	BOLULU	BOLULU CR.	1	0.1652

4. CONCLUSIONS AND RECOMMENDATIONS

This study has resulted in the production of rating curve sets, 3 - parameter rating equations and some skeleton rating tables for gauged Liberian rivers. Such information is necessary for the general process of water resources assessment for development, and will serve to facilitate data processing at the Liberian Hydrological Service. The curves, equation and tables also constitute a source of basic information on the nature of flow regimes of Liberian rivers at the various gauging stations.

Thirty-three stations representing the present strength of the Liberian Hydrological Network were scrutinized. For 24 stations having adequate data, rating equations are provided along with their individual periods of validity and range of stage applicable for such equations; basic information on the strength of the correlation is also provided.

The Hydraulic Method (Ref. 3) was used for rating curve derivation for 5 gauging stations which lacked adequate basic data. For these cases rational estimates of slope - roughness factors applicable for the cross-section are presented along with skeleton rating tables.

Neither the statistical nor hydraulic approaches proved appropriate for 4 stations in view of the inavailability of required input data, as are tabulated below:

TABLE 4.1 STATIONS WITHOUT RATING CURVE

CODE	NAME OF		NO. OF	PERIOD OF	REMARK
	STATION	RIVER	D. M.	OPERATION	ON D. M.
01 00 KL	KOLAHUN	KAIHA		1982-till now	
05 00 MC (T)	MT. COFFEE	KOIN CR.	1	1980-till now	low water value
06 R1 BN (T)	BENTOL	BENTOL CR.	2	1975	Abandoned
07 00 MF	MT. FINLEY	ST. JOHN	3	1957-1958	Abandoned

It is recommended that flow measurements be conducted for the first two stations for a full range of stage to facilitate statistical estimation of their rating curves. Where this exercise proves too expensive, one measurement necessarily conducted during flood and fulfilling the basic requirements for use of the hydraulic approach (Ref. 3) would suffice.

In five cases, the range of applicability to the rating curves is limited. For these stations more flow measurements are required as tabulated below:

TABLE 4.2 STATIONS FOR WHICH MORE FLOW MEASUREMENTS ARE URGENTLY NEEDED

CODE	NAME OF		RECOMMENDED
	STATION	RIVER	VALUE OF STAGE
02 01 BE	BENDUMA	MAFFA	HIGH WATER
01 00 BO(T)	BOLAHUN	WAWO CR.	WHOLE INTERVAL
07 L3 SC(T)	SACLAPEA	WEH CR.	HIGH WATER
10 R3 TA	TAPETA	GWEHN CR.	HIGH WATER
03 L3 LU	LUYEMA	LAWA	LOW WATER ($H \leq 50$cm)

One - sided tests of significance conducted on the correlation coefficient (R) failed to reject the null hypothesis of no correlation between the data points. Accordingly, critical values (Rc) were computed which are the minimum to be rationally accepted for the given sample sizes.

It was also shown that the hydraulic exponent (N) is physically related to the slope - roughness factor, channel geometry at the gauging cross-section and depth of flow. Accordingly, flow measurement cross-sections in Liberia are mostly quasi-rectangular ($1.000 \leq N \leq 1.666$) or quasi-trapezoidal ($1.666 \leq N \leq 2.666$). Still higher values of the physical parameter (N) can be expected, depending on the complexity of the cross-sectional geometry.

In the case of Baila (ST. JOHN RIVER), the value of N was noticed to have increased ten-fold between 1961 and 1975. To explain whether this increase is a result of possible drastic change in local channel geometry at this site, it is suggested that information from D.M notes be used to derive the physical exponent (N) as a function of gauge height. While the case of Baila is special, it should be noted that D. M. notes (with reference gauge height) serve to facilitate use of the hydraulic method from which not only rating curves are obtainable, but also information on the variation of slope - roughness with depth of flow; the latter information being essential to physical estimation of the magnitude of hydraulic exponent to be expected for a particular flow gauging cross-section. This is just why it is recommended that this type of information be organized at the Liberian Hydrological Service.

At Robertsport (FASA CREEK), it is advised that the head of water over the concrete weir be used to relate water-levels for the newly installed gauge to those obtained from the old installation.

5. REFERENCES

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