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Development of Deterministic Model between Peak Discharge(Qp) & Duration(D) of Unit Hydrograph and Comparison of 'US Army Corps of Engineers' recommendations with the present Study at Kharkai Barrage site on river Subarnarekha, India.

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Abstract: *The present study aims to develop an empirical model between Peak Discharge (Q_P) and Duration (D) of UG at Kharkai Barrage site on river Subarnarekha, India.* *The correlation coefficient between the parameters involved in the study is greater than 0.6. Hence, hydrological models can be done. Then mathematical relationships between the two parameters mentioned above have been developed by using Least Square Principle, Computer Programming and various software packages. The model has been chosen on the basis of least values of % deviation and Standard deviation of % deviation. For any Q_P value thus obtained from the developed model, the corresponding Stage value (G) can be computed from [Mukherjee, M.K and Sarkar, S, 2007].The stages may be obtained from Stage-Discharge models, corresponding to Q_P. Therefore, the values of Stages (G) thus obtained are on conservative side. If the presently adopted Danger level for 'Flood' for the river Subarnarekha at the gauging site, is lower than the stage computed from (G-Q) Model, then there is no problem. If the presently adopted 'Danger Level' for Flood for the river Subarnarekha at the gauging site, is higher than the stage computed from (G-Q) model , then the presently adopted danger level for floods needed to be changed. Therefore, emergency evacuation may be adopted by propagating well advanced 'Flood Warning' that may save thousands of lives from the fury of 'flood '. Moreover, peak discharge is a potential tool for the design of various Hydraulic Structures. Another investigation has been done here is the comparison of US Army Corps of recommendations of W_{50}, W_{75} and q with the unit hydrographs drawn here. It has been found that the ratioW_{50} / W_{75} are quite close to the US Army Corps of Engineers recommended value of 1.75 up to a particular duration. After that duration the value of the ratio decreases as the duration increases. However, an average value of the product W_{50} and $q^{1.08}$ was computed to be 1.95. It has been also noted that the values of the product W_{50} and $q^{1.08}$ are constant for a catchment. For the US Catchment it was found by 'US Army Corps of Engineers' that the constant is 5.87.*

Key Words: *Unit Hydrograph, Peak Discharge, Stage, Method of Super-position, Least Square Principle, Approximating Curve, correlation coefficient, 'US Army Corps of Engineers', 'Flood Warning'.*

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I. Introduction

The problem of predicting the flood hydrograph resulting from a known storm in a catchment has received considerable attention in the present time. A large numbers of methods have been proposed to solve this problem and of them probably the most popular and widely used method is unit hydrograph method. This method was first suggested by Sherman in 1932 and has undergone many refinements since then.

A unit hydrograph is defined as the hydrograph of direct runoff resulting from one unit depth (1 cm) of rainfall excess occurring uniformly over the basin and at a uniform rate for a specified duration.

The unit hydrograph method, notwithstanding its certain limitations, is greatly used in the development of flood hydrographs for extreme rainfall magnitudes for used in the design of hydraulic structures, extension of flood flow records based on rainfall records and development of flood forecasting and warning systems based on rainfall. The technique has also been successfully applied in hydrological studies for predicting Peak Discharge for a catchment, where the unit hydrographs for different durations can be prepared from the observed rainfall and runoff records for a given duration.

In the present study, a particular catchment was taken for investigation, i.e., the catchment of Kharkai Barrage Site. It is pertinent to mention here that the Kharkai Barrage is constructed on the river Subarnarekha (India) is an inter-state river flowing through Bihar, West Bengal and Orissa. It originates in the Chotanagpur plateau of Bihar and flows into Bay of Bengal. The upper part of the Subarnarekha and its tributaries run through the fertile lands of Bihar, but the farming in this region is mainly dependent on the inadequate rainfall, as the water resources of the river Subarnarekha is largely untapped. The upper basin, besides containing fertile land, also contains large reserves of minerals. A number of important industries have therefore grown along the banks of the river. Catchment characteristics such as, stream order, drainage density, stream density, length, shape, slope etc. was not available. Instead, a 6 hour unit hydrograph and area of the catchment for the Kharkai Barrage Site were used for the present study.

II. Procedure & Methodology

a) Processing of the Computer Output Data

By using the principle of superposition, the unit hydrograph of different durations have been obtained in Microsoft Excel. A Computer Program has also been developed for this purpose. Both results have been appeared to be same. Then from the computer output, the unit hydrographs of different durations for the catchment has been developed.

Then from the unit hydrograph thus developed, the Peak Discharge (Q_p) and Corresponding Duration (D) have been identified. Before use, the data has been statically checked for consistency and continuity.

b) Methodology for the developed of model

Then an attempt has been made to establish mathematical & graphical relationship between Peak Discharge (Q_p) and Corresponding Duration (D) of unit hydrograph. They are implemented by computer programming and various software packages.

Various mathematical equations (or approximating curves) have been attempted in the form of Straight Line Fitting, Logarithmic Fitting, Exponential Fitting, Polynomial Degree-2 Fitting, Polynomial Degree-3 Fitting and Power fitting for developing relationships and ultimately mathematical models between Peak Discharge (Q_p) & Corresponding Duration (D) of unit hydrograph have been developed. Final model has been selected by considering the satisfactory values of Average % Deviation, Standard Deviation of % Deviation and Correlation coefficient between the parameters involved in this study. Computer Programming and various software packages have been used for developing such mathematical relationships.

Field data is often accompanied by noise. Even though all control parameters (independent variables) remain constant, the resultant outcomes (dependent variables) vary. A process of quantitatively estimating the trend of the outcomes, also known as regression or curve fitting, therefore becomes necessary.

Nevertheless, for a given set of data, the fitting curves of a given type are generally not unique. Thus, a curve can be obtained by the method of least squares.

The method of least squares assumes that the best-fit curve of a given type is the curve that has the minimal sum of the deviations squared (least square error) from a given set of data.

Let the data points are (x_1, y_1), (x_2, y_2),…(x_n, y_n) where x is the independent variable and y is the dependent variable. The fitting curve f(x) has the deviation (error) d from each data point, i.e., $d_1=y_1-f(x_1)$, $d_2=y_2-f(x_2)$….$d_n= y_n-f(x_n)$. According to the method of least squares, the best fitting curve has the property that:

$$\Pi=d_1^2+d_2^2+\ldots+d_n^2=\sum d_i^2=\sum[y_i-f(x_i)]^2=\text{a minimum}$$

Computer Programming and various software packages have been used for developing such mathematical relationships.

Sample Calculations and Graph

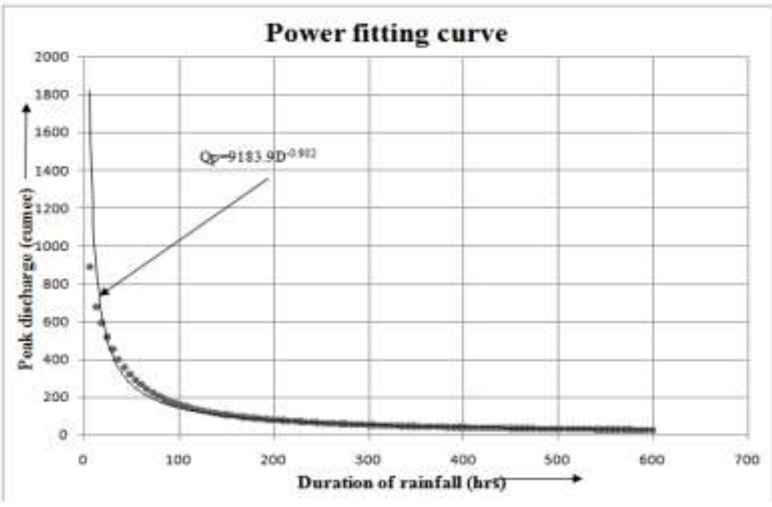

Table-I

POWER FITTING									
Duration of rainfall D (hrs)	Peak discharge(Q_P) (m3/s) (field data)	Peak discharge (Q_P) (computed)	Error	Absolute Error	% Devn	Average % Devn	Standrad Devn of % Devn	Co-relation coefficient RC1	Co-relation coefficient RC2
6	890	1824.46	-934.46	934.46	105.00	6.44	11.28	-0.69	0.60
12	680	976.35	-296.35	296.35	43.58				
18	594	677.28	-83.28	83.28	14.02				
24	519.25	522.49	-3.24	3.24	0.62				
30	454.4	427.23	27.17	27.17	5.98				
36	400.83	362.45	38.38	38.38	9.58				
42	357.57	315.40	42.17	42.17	11.79				
48	323.75	279.61	44.14	44.14	13.64				
54	293.67	251.42	42.25	42.25	14.39				
60	267.4	228.63	38.77	38.77	14.50				
66	243.91	209.80	34.11	34.11	13.99				
72	223.58	193.96	29.62	29.62	13.25				
78	206.38	180.45	25.93	25.93	12.56				
84	191.64	168.78	22.86	22.86	11.93				
90	178.87	158.60	20.27	20.27	11.33				
96	167.69	149.63	18.06	18.06	10.77				
102	157.82	141.67	16.15	16.15	10.23				
108	149.06	134.55	14.51	14.51	9.74				
114	141.21	128.14	13.07	13.07	9.25				
120	134.15	122.35	11.80	11.80	8.80				
126	127.76	117.08	10.68	10.68	8.36				
132	121.95	112.27	9.68	9.68	7.94				
138	116.65	107.86	8.79	8.79	7.54				
144	111.79	103.80	7.99	7.99	7.15				
150	107.32	100.04	7.28	7.28	6.78				
156	103.19	96.57	6.62	6.62	6.42				
162	99.37	93.34	6.03	6.03	6.07				
168	95.82	90.32	5.50	5.50	5.74				
174	92.52	87.51	5.01	5.01	5.42				
180	89.43	84.87	4.56	4.56	5.10				
186	86.55	82.40	4.15	4.15	4.80				
192	83.84	80.07	3.77	3.77	4.49				
198	81.3	77.88	3.42	3.42	4.20				
204	78.91	75.81	3.10	3.10	3.93				
210	76.66	73.86	2.80	2.80	3.66				
216	74.53	72.00	2.53	2.53	3.39				
222	72.51	70.25	2.26	2.26	3.12				
228	70.61	68.58	2.03	2.03	2.88				
234	68.79	66.99	1.80	1.80	2.62				
240	67.07	65.48	1.59	1.59	2.38				

246	65.44	64.03	1.41	1.41	2.15				
252	63.88	62.66	1.22	1.22	1.92				
258	62.4	61.34	1.06	1.06	1.70				
264	60.98	60.08	0.90	0.90	1.47				
270	59.62	58.88	0.74	0.74	1.25				
276	58.33	57.72	0.61	0.61	1.05				
282	57.09	56.61	0.48	0.48	0.84				
288	55.9	55.55	0.35	0.35	0.63				
294	54.76	54.52	0.24	0.24	0.43				
300	53.66	53.54	0.12	0.12	0.23				
306	52.61	52.59	0.02	0.02	0.04				
312	51.6	51.68	-0.08	0.08	0.15				
318	50.62	50.80	-0.18	0.18	0.35				
324	49.69	49.95	-0.26	0.26	0.52				
330	48.78	49.13	-0.35	0.35	0.71				
336	47.91	48.34	-0.43	0.43	0.89				
342	47.07	47.57	-0.50	0.50	1.06				
348	46.26	46.83	-0.57	0.57	1.23				
354	45.47	46.11	-0.64	0.64	1.41				
360	44.72	45.42	-0.70	0.70	1.56				
366	43.98	44.75	-0.77	0.77	1.74				
372	43.27	44.10	-0.83	0.83	1.91				
378	42.59	43.46	-0.87	0.87	2.05				
384	41.92	42.85	-0.93	0.93	2.22				
390	41.28	42.26	-0.98	0.98	2.36				
396	40.65	41.68	-1.03	1.03	2.53				
402	40.04	41.12	-1.08	1.08	2.69				
408	39.46	40.57	-1.11	1.11	2.81				
414	38.9	40.04	-1.14	1.14	2.93				
420	38.33	39.52	-1.19	1.19	3.11				
426	37.8	39.02	-1.22	1.22	3.23				
432	37.26	38.53	-1.27	1.27	3.41				
438	36.75	38.06	-1.31	1.31	3.55				
444	36.26	37.59	-1.33	1.33	3.67				
450	35.77	37.14	-1.37	1.37	3.83				
456	35.3	36.70	-1.40	1.40	3.96				
462	34.84	36.27	-1.43	1.43	4.10				
468	34.4	35.85	-1.45	1.45	4.21				
474	33.96	35.44	-1.48	1.48	4.35				
480	33.54	35.04	-1.50	1.50	4.47				
486	33.12	34.65	-1.53	1.53	4.61				
492	32.72	34.27	-1.55	1.55	4.73				
498	32.33	33.89	-1.56	1.56	4.84				
504	31.94	33.53	-1.59	1.59	4.98				
510	31.56	33.17	-1.61	1.61	5.11				
516	31.2	32.83	-1.63	1.63	5.21				
522	30.84	32.49	-1.65	1.65	5.34				

528	30.5	32.15	-1.65	1.65	5.42				
534	30.15	31.83	-1.68	1.68	5.56				
540	29.81	31.51	-1.70	1.70	5.69				
546	29.48	31.19	-1.71	1.71	5.82				
552	29.16	30.89	-1.73	1.73	5.93				
558	28.85	30.59	-1.74	1.74	6.03				
564	28.54	30.30	-1.76	1.76	6.15				
570	28.24	30.01	-1.77	1.77	6.26				
576	27.95	29.73	-1.78	1.78	6.35				
582	27.66	29.45	-1.79	1.79	6.47				
588	27.38	29.18	-1.80	1.80	6.57				
594	27.1	28.91	-1.81	1.81	6.68				
600	26.83	28.65	-1.82	1.82	6.79				

Table-II:

<table>
<tr><th colspan="9">SYNOPSIS OF RESULTS</th></tr>
<tr><th>Name of the river</th><th>Type of fitting</th><th>Developed Equation</th><th>Average % Deviation</th><th>Standard Deviation of % Deviation</th><th>RC1</th><th>RC2</th><th>Suggested Model</th><th>Remarks</th></tr>
<tr><td rowspan="6">SUBARNAREKHA</td><td>Linear</td><td>Q_p=-.5696D+280.99</td><td>103.06</td><td>388.36</td><td>-0.69</td><td>0.14</td><td rowspan="6">Q_P =9183.9* $D^{-0.902}$</td><td rowspan="6">The values of Average % Deviation and Standard Deviation of % deviation is least in case of Power fitting. Also the plotted curve is very satisfactory. Moreover, the correlation coefficient between the parameters involved in the study, for power fitting, are greater 0.6. Hence, the Power Equation has been chosen here as model.</td></tr>
<tr><td>Logarithmatic</td><td>Q_p=-145.6ln(D)+898.8</td><td>64.26</td><td>55.56</td><td>-0.69</td><td>-0.90</td></tr>
<tr><td>2nd degree polynomial</td><td>Q_p=.0028D^2-2.2723D+454.66</td><td>67.62</td><td>49.70</td><td>-0.69</td><td>-0.80</td></tr>
<tr><td>3rd degree polynomial</td><td>Q_p=-1E-05D^3+.0148D^2-5.2051D+606.44</td><td>520.35</td><td>691.48</td><td>-0.69</td><td>0.46</td></tr>
<tr><td>Power</td><td>Q_p=9183.9*$D^{-.902}$</td><td>6.44</td><td>11.28</td><td>-0.69</td><td>0.60</td></tr>
<tr><td>Exponential</td><td>Q_p=268.6$e^{-.005D}$</td><td>22.62</td><td>15.34</td><td>-0.69</td><td>-0.94</td></tr>
</table>

Application of US Army Corps Equations To the present Study:

As it is mentioned earlier that from the given 6-h UG, a number of unit hydrographs of different durations have been developed by using method of ‘Superposition’. Then the developed Unit Hydrographs were plotted by using software packages. Then from each Unit Hydrographs of each duration W_{50} and W_{75} were measured. Here detailed calculations have been furnished in the following Table: III.

Table-III

RELATIONSHIP BETWEEN W_{50} AND W_{75}						
AREA OF CATCHMENT (km^2)=		5725.08				
Duration of rainfall D (hours)	Peak discharge (Q_p) (cumec) (field data)	$q=Q_p/A$ (m3/s/km2)	W_{50} (hours) (from graph)	W_{75} (hours) (from graph)	W_{50}/W_{75}	$W_{50}xq^{1.08}$
6	890	0.16	12	7	1.71	1.61
12	680	0.12	18	11	1.64	1.80
18	594	0.104	22.5	15	1.5	1.95
24	519.25	0.091	27	18.5	1.46	2.02
30	454.4	0.079	32	23	1.39	2.07
36	400.8	0.070	37.5	26.5	1.42	2.12
42	357.57	0.062	44	31.5	1.40	2.20
48	323.75	0.057	46	35.5	1.30	2.07
54	293.67	0.051	53.5	41.5	1.29	2.16
60	267.4	0.047	60.5	46.5	1.30	2.21
66	243.1	0.042	66	52.5	1.26	2.18
72	223.58	0.039	72.5	59	1.23	2.18
78	206.38	0.036	78	65	1.2	2.16
84	191.64	0.033	84	71	1.18	2.14
90	178.87	0.031	90	77	1.17	2.13
96	167.69	0.029	96	83	1.16	2.12
102	157.82	0.028	102	88.5	1.15	2.11
108	149.06	0.026	108.5	94.5	1.15	2.11
114	141.21	0.025	114	100.5	1.13	2.09
120	134.15	0.023	120	107	1.12	2.08
126	127.76	0.022	126	112.5	1.12	2.07
132	121.95	0.021	132	119	1.11	2.07
138	116.65	0.020	138	125	1.10	2.06
144	111.8	0.020	144	131	1.10	2.05
150	107.32	0.019	150	137	1.09	2.05
156	103.19	0.018	156	143	1.09	2.04
162	99.37	0.017	162	149	1.09	2.03
168	95.82	0.017	169	155	1.09	2.04
174	92.52	0.016	174	161	1.08	2.02
180	89.44	0.016	180	167	1.08	2.02
186	86.55	0.015	192	179	1.07	2.08
192	83.84	0.015	194	179	1.08	2.03
198	81.3	0.014	198	185	1.07	2.00
204	78.92	0.014	204	191	1.07	2.00
210	76.66	0.013	211	197	1.07	2.00
216	74.53	0.013	216	203	1.06	1.99

222	72.51	0.013	222	209	1.06	1.98
228	70.6	0.012	228	215	1.06	1.98
234	68.8	0.012	234	221	1.06	1.97
240	67.08	0.012	240	227	1.06	1.97
246	65.44	0.011	246	233	1.06	1.97
252	63.89	0.011	252	239	1.05	1.96
258	62.4	0.011	256	245	1.04	1.94
264	60.98	0.011	264	251	1.05	1.96
270	59.63	0.010	270	257	1.05	1.95
276	58.33	0.010	276	263	1.05	1.95
282	57.08	0.010	282	269	1.05	1.94
288	55.9	0.010	288	275	1.05	1.94
294	54.76	0.010	294	281	1.05	1.94
300	53.66	0.009	300	287	1.05	1.94
306	52.61	0.009	306	293	1.04	1.93
312	51.6	0.009	312	299	1.04	1.93
318	50.62	0.009	318	305	1.04	1.93
324	49.68	0.009	324	312	1.04	1.92
330	48.78	0.009	329	317	1.04	1.91
336	47.91	0.008	336	323	1.04	1.92
342	47.07	0.008	342	329	1.04	1.92
348	46.26	0.008	347	335	1.04	1.91
354	45.47	0.008	354	341	1.04	1.91
360	44.72	0.008	361	347	1.04	1.91
366	43.98	0.008	365	354	1.03	1.90
372	43.27	0.008	371	359	1.03	1.90
378	42.59	0.007	379	366	1.04	1.90
384	41.92	0.007	384	372	1.03	1.90
390	41.28	0.007	391	378	1.03	1.90
396	40.65	0.007	396	383	1.03	1.89
402	40.04	0.007	401	390	1.03	1.89
408	39.46	0.007	407	396	1.03	1.88
414	38.88	0.007	414	402	1.03	1.89
420	38.33	0.007	421	408	1.03	1.89
426	37.79	0.007	425	414	1.03	1.88
432	37.26	0.007	431	419	1.03	1.88
438	36.75	0.006	438	426	1.03	1.88
444	36.26	0.006	444	432	1.03	1.88
450	35.77	0.006	451	438	1.03	1.88
456	35.3	0.006	455	444	1.02	1.87
462	34.84	0.006	462	450	1.03	1.87
468	34.4	0.006	468	456	1.03	1.87
474	33.96	0.006	473	460	1.03	1.86
480	33.54	0.006	480	466	1.03	1.86

486	33.12	0.006	487	472	1.03	1.87
492	32.72	0.006	492	476	1.03	1.86
498	32.32	0.006	499	485	1.03	1.86
504	31.94	0.006	501	491.5	1.02	1.85
510	31.56	0.006	508	497	1.02	1.85
516	31.2	0.005	516	504	1.02	1.85
522	30.84	0.005	521	508	1.03	1.85
528	30.49	0.005	530	515	1.03	1.86
534	30.15	0.005	533	522	1.02	1.84
540	29.81	0.005	540	527	1.02	1.85
546	29.48	0.005	546	532	1.03	1.84
552	29.16	0.005	551	540	1.02	1.84
558	28.85	0.005	556.5	544	1.02	1.84
564	28.54	0.005	565	551.5	1.02	1.84
570	28.24	0.005	569	556	1.02	1.84
576	27.95	0.005	575	563	1.02	1.83
582	27.66	0.005	580	566	1.02	1.83
588	27.38	0.005	588	575.5	1.02	1.83
594	27.01	0.005	592	580	1.02	1.82
600	26.83	0.005	600	588	1.02	1.83
					Average=	1.95

III. Conclusion:

- Peak Discharge (Q_P) is a potential tool for designing important Hydraulic Structures such as Concrete Gravity Dam, Weir, Barrage, Bridge across the river, Guide Banks ete .
- The developed model between Q_P and D and Synopsis of results are shown in Table-I and Table-II respectively. For any given value of D, Q_P can be readily ascertained, without any instrumentation, expensive and time consuming field work.
- The power model has been chosen here because the Average % Deviation and Standard Deviation of % Deviation are least in this case. [Table-I].
- Also the values of co-relation co-efficient are ranging between 0.6 and 1 which is very satisfactory for any Hydrological Modelling. [Table-I].
- For any Q_P value thus obtained, the corresponding Stage value (G) can be computed from [Mukherjee, M.K and Sarkar, S, 2007].
- The stages may be obtained from Stage-Discharge models, corresponding to Q_P. Therefore, the values of Stages (G) thus obtained are on conservative side.
- If the presently adopted Danger level for 'Flood' for the river Subarnarekha at the gauging site, is lower than the stage computed from (G-Q) Model, then there is no problem.
- If the presently adopted 'Danger Level' for Flood for the river Subarnarekha at the gauging site, is higher than the stage computed from (G-Q) model , then the presently adopted danger level for floods needed to be changed.
- Therefore, emergency evacuation may be adopted by propagating well advanced 'Flood Warning' that may save thousands of lives from the fury of 'flood '.
- Again it has been found from Table-III that after particular duration, the values of the ratioW_{50} / W_{75} are quite close to the US Army Corps of Engineer recommended value of 1.75.After that duration the value of the ratio decreases as the duration increases. Hence, it can be concluded that the value of the ratio does not remain constant for all durations. Probably this is the reason for which Snyder introduced the concept of Standard Rain.
- It was also found from the Table-III that the values of the product of W_{50} and $q^{1.08}$ were ranging from 1.67 to 2.21 for the catchment under study. However, an average value of the product W_{50} and $q^{1.08}$ was

computed to be 1.95. It is to be noted that the value of the product W_{50} and $q^{1.08}$ is constant for a catchment. For the US Catchment it was found by 'US Army Corps of Engineers' that the constant is 5.87.

Notations used in the Paper:

- G - Stage
- Q_P - Peak Discharge of Unit Hydrograph
- UG - Unit Hydrograph
- D - Duration of Unit Hydrograph
- Devn. - Deviation
- RC1 - Correlation co-efficient between Peak Discharge (field data) (Q_P) and Duration (D) of Unit Hydrograph.
- RC2 - Correlation co-efficient between Peak Discharge (computed data) (Q_P) and Duration (D) of Unit Hydrograph.
- W_{50} - Width of unit hydrograph in h at 50% peak discharge
- W_{75} - Width of unit hydrograph in h at 75% peak discharge
- q - Q_P/A = Peak Discharge per Unit catchment area
- A - Catchment area

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