THE DESIGN OF STORM-WATER DRAINS.

PRELIMINARY PAPER.

BY JAMES VICARS, M.E. (Sydney).

(A Paper read before the Sydney University Engineering Society, on August 9th, 1911.

This paper is intended to be preliminary to the design of a system of storm-water drains, and will therefore deal with the flood discharge from catchment areas. This is not the simple problem which it may appear, and it is remarkable how many authorities have essayed its solution, and how varied are the conclusions. Therefore, it is essential at the outset to devote ample consideration to the subject to obtain a clear conception of it so that a fair start can be made. It would seem that every one who has given much consideration to the problem has come to the conclusion that all other investigators have erred through their failure to properly evaluate the various factors which are involved, through insufficient data, etc., and have added still another formula to an already formidable list.

Some have devised formulæ entirely empirical and probably intended for purely local application; others have constructed formulæ from examples of successful practice embracing a wide range of variation in conditions; whilst others, again, have attempted the solution in a more or less entirely rational manner. Very great difficulties are experienced in assigning probable values for effective average intensity of rainfall over the catchment area; the factor to be employed for the average effects of absorption, evaporation, slope of surface, and nature of catchment, such as forest growth, grassed land, plain or rocky surface, and for shape of catchment. On all these the flood discharge may depend, and frequently in general practice the most of these absolutely are not known and cannot be approximately determined or even guessed.

Is it, then, not futile to attempt a solution?

In some instances monsoonal or tropical rains even of less intensity than the maximum on record may be more generally distributed, last longer, and produce a higher average for the whole catchment. Again, in other localities a cyclonic or anti-cyclonic storm may produce this result. On the other hand a storm of high maximum intensity and great variation has resulted in a maximum rate of discharge. The steeper the slope and harder and barer the surface the less the evaporation and absorption; the more the vegetation and forest growth or tion and the less the velocity of flow on even steep slopes, sandy or free the character of the soil, the greater the absorp-whilst high winds increase evaporation.

Does this formidable list not warrant the statement that any approximate solution at all is impossible without an infinitely more complex formula than Kutter's for the flow of water in pipes?

As often happens in the investigation of physical problems, a solution may be sought by ascertaining the combined effect of all the above elements operating at the same time; and, after all, it is not the value of the individual elements with which one is concerned.

Of course the analysis of the provisions made in the case of successful schemes of drainage affords invaluable data; and of equal value are the records of failures from insufficient provisions, which disclose errors in assigned values of co-efficients or fundamental errors in accepted formulæ, or bring to light exceptional circumstances which, but for the disaster, might have escaped record, or been impossible of determination. The gauging of run-off from catchment areas for water supplies are also valuable, and are usually ascertainable with tolerable accuracy.

It is generally assumed that a maximum rate of rainfall should be a factor, but whether for five or ten minutes, an hour or longer, there is by no means a consensus of opinion. The area is always a factor. Several formulæ include terms of slope of surface and ratio of length to breadth of catchment, but only a very few of the authorities, and perhaps the best, consider one or other of them essential. The values assigned by their authors to these two elements have not, however, met with general approval, and are in certain cases impossible. On the other hand, some assign a constant value to rainfall, but they intended such formulæ for purely local application.

The following is a list of some of the better known formulæ:—

TABLE I.

AUTHOR.	FORMULA.
Col. Dickens ...	$Q = 100\ C\ M^{\frac{3}{4}} = 825\ M^{\frac{3}{4}}$
	$Q = 27\ C\ M^{\frac{1}{2}}$ $\quad C = 8{\cdot}25$

Ryves ... ... $Q = C\,M^{\frac{2}{3}}$ $\qquad C = 400$ to 650

Fanning ... ... $Q = 200\,M^{\frac{5}{6}}$

Burge ... ... $Q = \dfrac{1300\ M}{(\text{Length in Miles})^{\frac{2}{3}}}$

Dredge ... ... $Q =$ " "

Jackson ... ... $Q = \dfrac{C\ \&\ \text{Breadth}}{\text{Length}}\ A^{\frac{3}{4}}$

Steane ... ... $Q = \dfrac{181 \times \text{Area in sq. chains}}{1800\ (\text{Length in Chains})^{1\cdot23}}$

Craig ... ... $Q = 440\ B\ N \text{ hyp log } \dfrac{8\ L^2}{B}$ $\qquad N = 1\cdot16$

O'Connell... ... $Q = 45\cdot796 + (2097\cdot28 \times 457\cdot96\ A)^{\frac{1}{2}}$

McComb ... ... $Q = 5\cdot29375\ A^{\frac{3}{4}}$

Burkli Ziegler ... $Q = C\ R\ S^{\frac{1}{4}}\ A^{\frac{3}{4}}$ $\qquad S =$ slope in ft. per 1,000
$C = \cdot75$ to $\cdot31$

McMath ... ... $Q = C\ R\ S^{\frac{1}{5}}\ A^{\frac{4}{5}}$

" $\qquad Q = 2\cdot448\ R\ S^{\frac{1}{5}}\ A^{\frac{4}{5}}$

Adams ... ... $Q = A\ C\ R\ \dfrac{S}{(A^2R^2)_{\frac{1}{12}}} = C\ R^{\frac{5}{6}}\ A^{\frac{5}{6}}\ S^{\frac{1}{12}}$ $\quad C = 1\cdot035$

Hawksley ... $Q = A\ C\ R\ \left(\dfrac{.S}{A\ R}\right)^{\frac{1}{4}} = C\ R^{\frac{3}{4}}\ A^{\frac{3}{4}}\ S^{\frac{1}{4}}$ $\qquad C = 3\cdot946$

Chamier ... ... $Q = A\ C\ R\ \left(\dfrac{M^{\frac{3}{4}}}{M}\right) = 5\cdot03\ \ C\ R\ A^{\frac{3}{4}}$

Kernot ... ... $a = C\ M^{\frac{3}{4}}$ $\qquad C = 40$ to 80

Myers ... ... $a = C\ A^{\frac{1}{2}}$ $\qquad C = 1$ to 4

Talbot ... ... $a = C\ A^{\frac{3}{4}}$ $\qquad C = \frac{1}{3}$ to 1

Peck ... ... $a = \dfrac{A}{C}$ $\qquad C = 4$ to 6

Cleeman ... ... $a = C\ A^{\frac{1}{2}}$ $\qquad C = 1$ to 1.6

Steane ... ... $a = A^{0.62}$

$Q =$ Cubic ft. per sec.
$R =$ Rainfall in inches, per hr.
$a =$ area of waterway in sq. ft.
$M =$ Area of catchment in sq. miles
$A =$ " " acres
$C =$ variable co-efficient

Rejecting all formulæ which do not take into consideration the variation in intensity of rainfall, only five remain, and of these four make provision for slope of surface. One assigns to rainfall a value of $R^{\frac{3}{4}}$, one $R^{\frac{5}{6}}$, and three simply R. Again, two make the value of surface slope vary as $S^{\frac{1}{4}}$, one as $S^{\frac{1}{5}}$ and one as $S^{\frac{1}{12}}$, When S varies between .0001 and .04 the $S^{\frac{1}{4}}$ makes the discharge vary from 1 to nearly 4.5, while $S^{\frac{1}{12}}$ makes the variation range from 1 to 1.65. It can at once be stated that both cannot be correct; but when both authors are of equal weight and opportunity, it might reasonably be expected that one might adopt either with safety. Further, the values assigned to the area factor vary from $A^{\frac{3}{4}}$ to $A^{\frac{4}{5}}$ to $A^{\frac{5}{6}}$ which, for a catchment area of 100,000 acres, give values of 5,600 to 10,000 to 14,700 respectively. Such results surely indicate some fundamental error! In spite of this great diversity in the values of all fators, the resulting values of run-off determined by either one of the best four formulæ—Burkli Ziegler, McMath, Adams, and Hawksley—give comparable results for a rainfall up to 4in. per hour and for areas up to 10,000 acres.

It was felt, however, that the above illustrated diversity did not inspire confidence in the use of any one of the formulæ in general practice, and as the writer's experience furnished considerable data on this subject, he attempted an analysis according to his conception of the problem. It was decided that values for the ratio of length to breadth, and for slope of surface, could not be directly included in a simple formula, even if at all necessary. For assume a uniform rainfall over the whole catchment area having a length of one hundred chains and width of one chain, and assume that the rain continues during the time taken by flood waters in travelling from top of catchment to outlet, then the discharge clearly becomes equivalent to 100 times the average rainfall over one square chain, i.e., directly proportional to R x A, or, to the area alone—no matter what the slope or nature of surface may be. The same result is obtained if the storm is assumed to travel in advance of, and at the same rate as flow. Perhaps a rare occurrence, but nevertheless a result which may be approximated in large areas and is certainly attained in small ones.

To further illustrate the effect of the factor R the following table has been worked out:—

R equals	3	4	5	6 inches
$R^{\frac{3}{4}}$ equals	2.28	2.83	3.33	3.82
$R^{\frac{5}{6}}$ equals	2.5	3.18	3.82	4.45
.7R equals	2.1	2.8	3.5	4.2
.75R equals	2.25	3.0	3.75	4.5

The above table shows that by assigning a suitable coefficient to R the result can be made to differ by only about

5 per cent. from any of the factors adopted by the various authors for a rainfall up to 5in., and 10 per cent. for 6in. rainfall. There can, therefore, be no practical advantage in adopting the more cumbersome factor. Perhaps the Burkli Ziegler formula is the best for general application, but as has been shown, the adoption of a definite value for S, the slope of surface is certainly a fault in the case of small areas, and most likely in large ones. Indeed, for small areas, the calculated run-off might amount to several times the equivalent of the actual rainfall.

For the reasons adduced, it is considered that the maximum volume of flood flow depends directly on the rainfall—R, the area =A, and probably inversely on evaporation and absorption and unequal distribution which may be represented by the factor $\frac{1}{A^{\frac{1}{4}}}$ or inversely as the square root of the average distance from outlet waterway to boundary of catchment.

A maximum flood flow has frequently been experienced, especially in large catchments, at times of heavy general rain, not of maximum intensity, after the surface soil has become charged by previous rain. It would not, however, be correct on this account, to reduce the value of R and insert a variable factor for absorption; for the rain previously absorbed may be considered equivalent to an increase in the rainfall, i.e., the value of R becomes practically equivalent to the maximum.

A general formula may then be adopted as follows:—

Let r equal maximum rate of rainfall in inches per hour, gauged over ten minutes, or inches per 24 hours (actual fall).

A equal area of catchment in acres.

Q equal maximum rate of flood discharge in cubic feet per second.

a equal area of waterway to be provided in sq. ft.

c equal co-efficient for nature of catchment = 0.75 for paved surface as in a city, and steep open country; 0.5 for open grassed country; .0.3 for sandy loam soil and heavily timbered country.

v equal velocity of flow in outlet waterway in feet per second.

D equal diameter of drain in feet.

$$Q \text{ equal } \frac{c\ r\ A}{A^{\frac{1}{4}}} \text{ equal } c\ r\ A^{\frac{3}{4}}$$

$$a \text{ equal } \frac{Q}{v} \text{ equal } \frac{c\ r\ A^{\frac{3}{4}}}{v}$$

$$D \text{ equal } \frac{c^{\frac{1}{2}}\ r^{\frac{1}{2}}\ A^{\frac{3}{8}}}{(\cdot 7854v)^{\frac{1}{2}}} \text{ equal } 1{\cdot}13\ \frac{c^{\frac{1}{2}}\ r^{\frac{1}{2}}\ A^{\frac{3}{8}}}{v^{\frac{1}{2}}}$$

To avoid the necessity of, and uncertainty in, the selection of values of c, it was sought to modify the formula so as to embrace large as well as small catchments, maintaining the value of c constant. Curves were accordingly plotted for values of Q when C = 1.0, 0.8, 0.6, and 0.4, and a mean curve was determined which at every point gave full values, but not excessively full values for all areas. The curve corresponded to the formula: $Q = 1.57\ C\ r\ A^{\frac{2}{3}}$, giving results equivalent (in original formula) to c=1.0 up to 1,000 acres, c=0.6 up to 100,000 acres, and c=0.4 up to 10,000,000 acres.

The value of 1.57 when C=1 gives volumes of flow 50 per cent. above the possible for one acre, reaching 70 per cent. of full value at about 10 acres, and above 10 acres the results are about 25 per cent. higher than the writer's records. It is a good formula for general use.

Instead of r the writer prefers to adopt $\left(\frac{R}{2}\right)^{\frac{1}{2}}$ where R=the average annual rainfall in inches. It is believed that values of R are more reliable and accessible than values of r.

Substituting $\left(\frac{R}{2}\right)^{\frac{1}{2}}$ for r in the formula given and inserting, a co-efficient C varying according to locality as for tropical, sub-tropical, or temperate zones, etc.,

$$Q = 1{\cdot}11\ C.R.^{\frac{1}{2}}\ A^{\frac{2}{3}} = 1{\cdot}57\ c\ r\ A^{\frac{2}{3}}$$

A value of 0.9 for C is suggested as ample for Australian conditions in the absence of data for higher latitudes.

(1) $$\text{Then } Q = R^{\frac{1}{2}}\ A^{\frac{2}{3}} = 1{\cdot}414\ r\ A^{\frac{2}{3}}$$

$$a = \frac{R^{\frac{1}{2}}\ A^{\frac{2}{3}}}{v} = \frac{1{\cdot}414\ r\ A^{\frac{2}{3}}}{v}$$

$$D = \frac{1{\cdot}13\ R^{\frac{1}{4}}\ A^{\frac{1}{3}}}{v^{\frac{1}{2}}} = \frac{1{\cdot}342\ r^{\frac{1}{2}}\ A^{\frac{1}{3}}}{v^{\frac{1}{2}}}$$

or, adopting C=0.8 as representing maximum percentage of run off:

(2) $$Q = {\cdot}9\ R^{\frac{1}{2}}\ A^{\frac{2}{3}} = 1{\cdot}26\ r\ A^{\frac{2}{3}}$$

$$a = \frac{{\cdot}9\ R^{\frac{1}{2}}\ A^{\frac{2}{3}}}{v} = \frac{1{\cdot}26\ r\ A^{\frac{2}{3}}}{v}$$

$$D = \frac{1{\cdot}07\ R^{\frac{1}{4}}\ A^{\frac{1}{3}}}{v^{\frac{1}{2}}} = \frac{1{\cdot}27\ r^{\frac{1}{2}}\ A^{\frac{1}{3}}}{v^{\frac{1}{2}}}$$

These arbitrary limits for the value of c=1.0 up to 1,000 acres; 0.6 to 100,000 acres, and 0.4 to 10,000,000 acres, have their drawbacks, for to use the formula intelligently one must remember the limits and be convinced that the nature of catchment falls within these limits. The volume of flood flow per acre diminishes as the area of catchment increases, other things remaining the same. This is no doubt due to the average

TABLE II.

AREA OF WATERWAYS.—James Vicars, M.C.E.

Locality.	Character	Aver'ge Annual Rainfall	Area of Catchment	Provided	Area of Waterway. Kernot's Formula	Area of Waterway. Formula (1)	Area of Waterway. Formula (4 & 5)	Remarks
		R. In's	A. Acres	Square Feet				
Bridgewater, Tasmania	Steep and Rocky	20	1,500	13 170	75	98 v = 6	110 v = 6	Failed Ample
Bendigo Creek, Sandhurst, Vic.	Undulating, lightly timbered	25	10,240	190 370	330	393 v = 6	367 v = 6	Failed Ample
Cootamundra, N.S.W.	1-3rd Hilly 2-3rds Undulating or Flat, moderately timbered	20	12,800	53	380	408 v = 6	467 v = 6	Failed
Moonee Ponds, Victoria	Slightly undulating, very little timber	25	32,000	1,000	752	840 v = 6	1,017 v = 6	Ample
Plenty River, Victoria	Small portions steep & densely timbered, remaining undulating and open ...	30	38,400	440	864	1,040 v = 6	1,380 v = 6	Failed
Merri Creek, Victoria	Undulating and lightly timbered	25	83,200	1,500	1,540	1,585 v = 6	1,800 v = 6	Ample
Saltwater River, Victoria	Generally open and lightly timbered	30	358,400	4,500	4,600	4,606 v = 6	5,500 v = 6	Ample
Yarra River Victoria	All Timbered—mountainous	35	960,000	8,000	9,640	9,595 v = 6	11,333 v = 6	Ample
Barwon River, Geelong, Vic.	Lightly Timbered — undulating	25	1,062,400	8,000	10,400	8,676 v = 6	8,730 v = 6	Small
Barwon River Railway Bridge	Lightly Timbered — undulating	25	1,075,200	4,000	10,496	8,730 v = 6	8,800 v = 6	Failed
Sturt Street, Adelaide, S.A.	Paved Surface and Buildings Slope, 1 per cent. ...	20	16	1·75 4·5 1% grade	2·7	4.7 v = 6	4·6—3·8 v = 6	Too Small Ample
Morphett Street, Adelaide, S.A.	Paved Surface and Buildings Slope, 1 per cent. to 3 per cent.	20	35	3 5·3 1·5% grade	4·8	4·9 v = 10	5—4·2 v = 10	Too Small Ample
Symonds' Place, Adelaide, S.A.	Paved Surface and Buildings Slope, 1 per cent. ...	20	56	7 10·8 grade 1%	6·8	10·9 v = 6	11·8—9·9 v = 6	Too Small Ample
East Terrace, Adelaide, S.A.	Paved Surface and Buildings Slope, 1 per cent. to 2 per cent.	20	50	4.9 1·4% grade	6·3	5·1 v = 12	5—4.5 v = 12	Ample
Victoria Park, Adelaide, S.A.	2-3rds Park Lands 1-3rd Residential Suburban	20	300	36 ½% grade	24	28·7 v = 7	35—29 v = 7	Ample
Torrens River, South Australia	Very Hilly—lightly timbered	30	115,200	1,550	1,900	2,161 v = 6	2,400—2,200 v = 6	Equivalent section of flood at 6 feet per sec.

intensity of rainfall diminishing as area increases. It is therefore the more general practice to maintain the rate of rainfall constant in each individual case and to determine the average value by assigning some fractional power to the factor representing the area, i.e., to determine the equivalent area which would produce an equal flood flow under maximum intensity of rainfall. Now, whether it is due to peculiarities in the distribution of rainfall under actual natural conditions or that percolation, absorption, and evaporation play the chief part, or whether and to what relative extent all these causes operate in the final result, it is difficult to say; but it appears that the equivalent area referred to does not vary in actual practice in so simple a manner. In fact, it seems that the more correct view is that the value of power index of area does not remain constant, but becomes less as the area increases. It is not easy to compass actual results by a simple formula of this kind, but for working by logarithms the average values may be approximated by the following special formula:—

(3) $$\log Q = (\cdot 78 + 0\cdot 01\, r^{\frac{1}{2}} - 0\cdot 02 \log A) \log A + \log r$$

(4) $$\log Q = (\cdot 82 - 0\cdot 02 \log A) \log A + \log r$$

(5) $$\log Q = (\cdot 82 - 0\cdot 02 \log A) \log A + \log R - \cdot 9$$

Formula (3) is the complex one previously alluded to, but which seems to the writer to embody all necessary considerations better than any other, and is believed to be very reliable. Formula (4) represents a fair maximum value of (3) and results obtained by it may be considered full. Formula (5) is a modification of (4) to annual rainfall, but does not take into consideration phenominal falls, which may be done by (3) or (4).

Table No. 2 illustrates the application of formulæ (1) (4) (5) in actual practice. In the majority of the examples cited the velocity of flow is not known, and has been assumed at 6ft. per second, which is safe in these cases for his formula according to the late Professor Kernott. The Adelaide data are from the writer's practice, all others being taken from a paper by the late Professor Kernott, on "Waterways of Bridges and Culverts."

In the case of the Torrens River catchment, the flood discharge was accurately gauged. At top flood the water flowed above crest of weir 8ft. deep, the crest being 132ft. long and 9ft. wide and level. At the same time, six sluices, each 3ft. diameter and 26ft. long, were carrying off water under an effective head of 18ft.

The formula has been put forward as an honest attempt to deal simply and comprehensively with a very vexed question, and it is believed to be more reliable than any other, simpler, and that it lends itself to more rational and general application.

Diagram No. 1 Comparison of Formulæ.

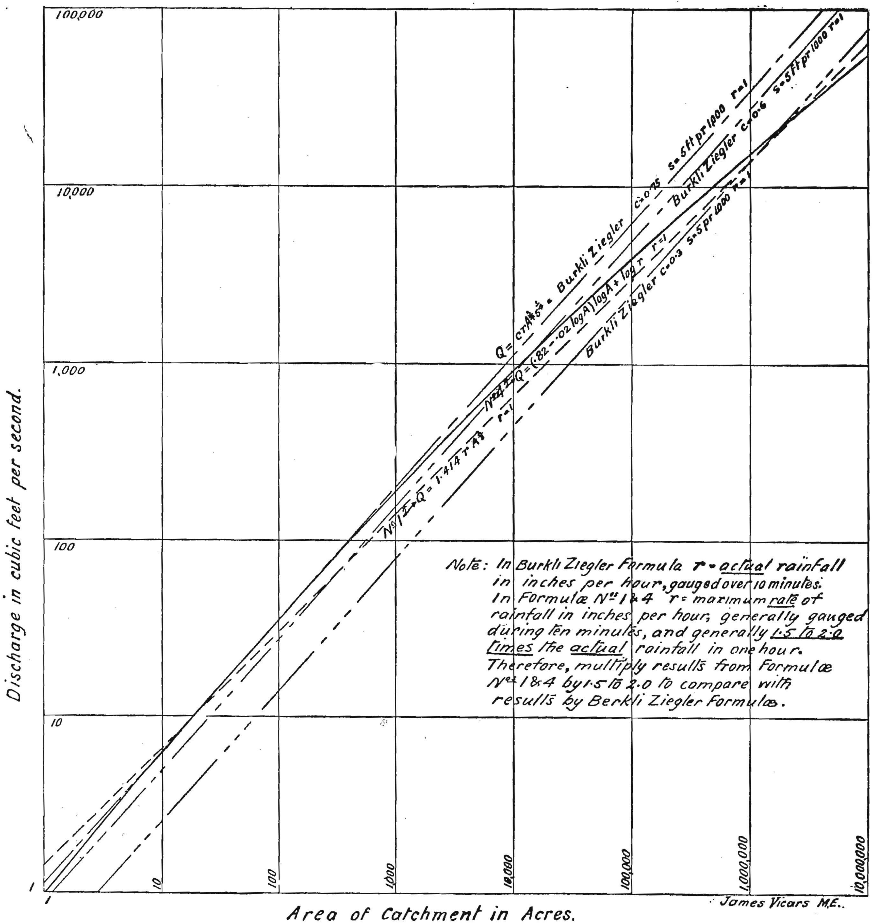


Diagram No. 2 Discharges by Formula No. 3 $Q = (\cdot 78 + \cdot 01 r^{\frac{1}{2}} - \cdot 02 \log A)\log A + \log r$.

r = Maximum rate of rainfall in inches per hour, gauged over 10 minutes.
= Actual rainfall in inches for 24 hours.

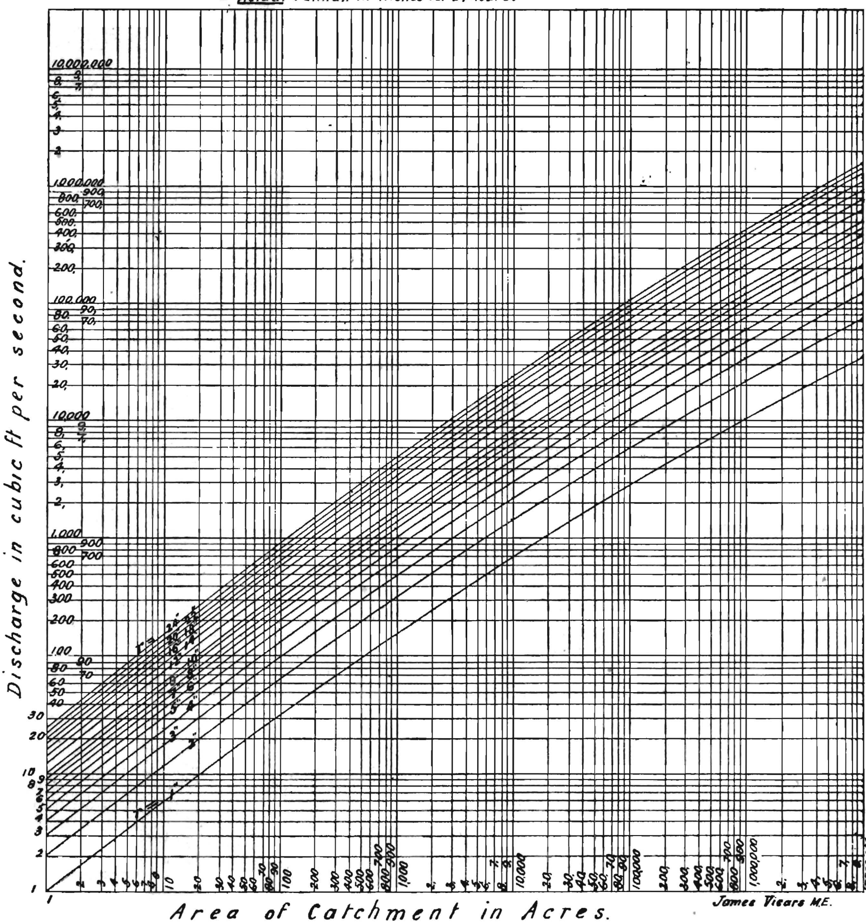
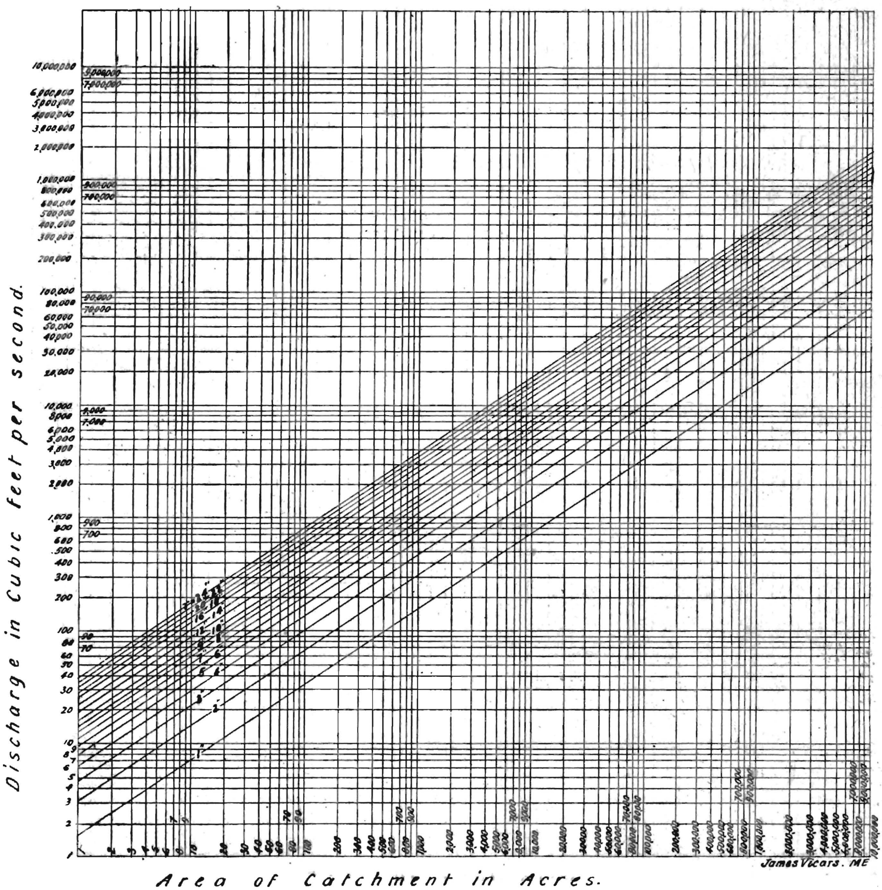
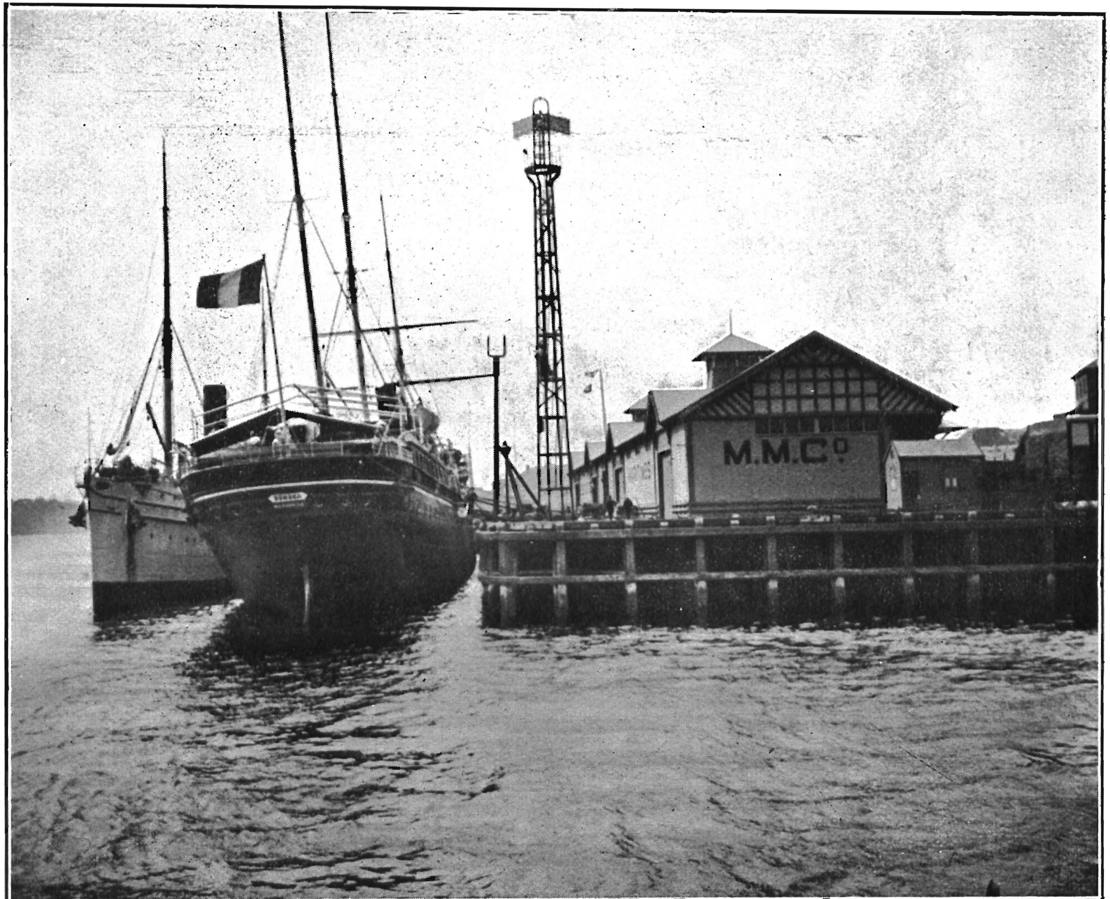


Diagram No 3. Discharges by Formula $Q = 1{\cdot}571\, r A^{\frac{2}{3}}$

r = Max: rate of rainfall in inches per hour, gauged over 10 minutes.

* Actual rainfall in inches in 24 hours.





M. M. Co's. Wharf, Miller's Point, Sydney.