No. 1,153.—“On the Results of a series of Observations on the Flow of Water off the ground in the Woodburn District, near Carrickfergus, Ireland ; with Rain-gauge Registries in the same locality, for a period of twelve months, ending 30th June, 1865.”
By ROBERT MANNING, M. Inst. C.E.

FOR the last fourteen years the water supply of Belfast has been very insufficient, and every available source has been reported upon and discussed. Finally, during the last Session of Parliament an Act was obtained empowering the execution of a plan for procuring water from near Carrickfergus, and of this scheme, the Woodburn rivers formed a considerable part. The Author was engaged, during the progress of the Bill, by one of the principal proprietors of water-rights on those rivers, and found it necessary to make frequent gaugings of the flow off the ground, and to register the rainfall of the district. Being aware of the utility of such observations to hydraulic Engineers, and that the Council of this Institution had, for some years past, invited communications on the subject, he continued the observations after the immediate necessity for doing so had ceased, and he now begs leave to submit the results to the notice of the Members.

It is not intended either to give a description of the proposed supply to Belfast, or to examine from a meteorological point of view, the data collected ; but merely to report the facts accurately, and to draw attention to such results as appear to be of practical moment.

In Plate 24 are shown the courses of the two branches of the Woodburn river, and the extent of the rain basin ; the elevation varies from 500 to 1,000 feet. The surface is chiefly composed of bare mountain pasture and grazing land, the upper rock being almost entirely tabular trap, overlying the chalk, with here and there patches of green sand.

Three gauges were placed respectively 300 feet, 750 feet, and 900 feet above the level of the sea, at the points marked on the plan ; and two stream gauges were erected, one on each branch of the stream, the positions of which are also indicated. The receiver of each rain gauge was placed about 2 feet above the surface, and was 10 inches in diameter ; the body of the gauge was of the same size, and from a float within it, the observations were made by a rod divided into inches and tenths. The stream gauges were rectangular notches with sharp edges, such as were used by

Mr. Francis, in his well-known experiments at Lowell, and the formula for calculating the discharge was

$$Q = 200 (L - 0.1 n H) H^{\frac{3}{2}}$$

where

Q = the quantity of cubic feet per minute,

L = the length of the notch in feet,

H = the head in feet,

and

n = the number of end contractions.¹

When the notch is the full width of the stream, $n = 0$, and the formula is simply

$$Q = 200 L \sqrt{H^3}.$$

differing from that in general use only in the coefficient, which is 7 per cent. less. It was employed in the present case in order to avoid all risk of exaggeration.

The notch on the southern branch of the stream received the drainage of 2,076 acres; that on the northern branch of 1,329 acres. Daily observations were taken at both, for the year ending June 30th, 1865; and weekly observations were made of the rainfall at all the three gauges before described. The rain gauge at Queen's College, Belfast, nine miles south of the district, where a daily registry had been kept for fourteen years, was used as a standard.² A summary of the results is given in Table No. 1, page 460.

The main facts thus collected are as follows:—The rainfall for the twelve months ending June 30th, 1865, was 35·867 inches, being nearly 18 per cent. above the rainfall at Belfast, which was only 30·5 inches. For the six months from November to May, the rain and the flow were respectively 14·766 inches, and 14·351 inches; the flow in December and January exceeding the rain by 0·927 inch. From May to November these quantities were 21·101 inches and 7·357 inches; the total loss on the year's rain being 14·159 inches. The minimum flow off 1,000 acres occurred in August, and amounted to 11 cubic feet per minute; the maximum was in September, and was as high as 3,180 cubic feet per minute. The mean monthly flow was at its minimum in July, and was 29 cubic feet per minute, attaining its maximum in November, when it was ten times that quantity. The year's rainfall, at an elevation of 900 feet, was 35·9 inches, at 750 feet it was 36·3 inches, and at 300 feet it was 35·4 inches.

These particulars having been ascertained, it was assumed that

¹ For a full explanation of this formula, *vide* "Lowell Hydraulic Experiments," by J. B. Francis. 4to. Boston, 1855.

² The observations, nearly 800 in number, may be consulted at the Institution.

TABLE No. 1.

MONTHS.	Rainfall.					Run off.	Loss.	Mean Monthly Flow off 1,000 Acres in Cubic Feet per Minute.
	Queen's College.	Woodburn.						
		65 ft.	900 ft.	750 ft.	300 ft.			
1864.								
July . .	1·650	1·9	1·8	1·8	1·833	0·361	1·472	29
August .	2·396	4·2	4·6	4·4	4·400	0·531	3·869	43
September	2·526	4·5	4·6	4·6	4·567	2·551	2·016	214
October .	3·370	5·0	5·1	4·5	4·867	2·412	2·455	197
November.	3·606	3·9	3·9	4·1	3·967	3·460	0·507	291
December.	1·586	2·3	2·5	1·9	2·233	2·712	+·479	221
1865.								
January .	4·147	2·7	2·4	3·2	2·767	3·215	+·448	261
February .	3·001	2·7	2·9	2·6	2·733	2·312	0·421	238
March . .	2·879	2·1	2·2	2·7	2·333	2·184	0·149	178
April . .	0·461	0·9	0·7	0·6	0·733	0·468	0·265	39
May . .	3·914	4·0	4·0	3·6	3·867	1·103	2·764	90
June . .	0·964	1·7	1·6	1·4	1·567	0·399	1·168	33
	30·500	35·9	36·3	35·4	35·867	21·708	14·159	
Winter .	15·680	..	..	..	14·766	14·351	0·415	1st Nov. to 1st May.
Summer .	14·820	..	..	..	21·101	7·357	13·744	1st May to 1st Nov.

the rainfall on the Carrickfergus mountains bore a constant ratio to that at Belfast. The exact proportion for the year 1864-5 was 1,176 to 1,000; but the same care was taken to avoid exaggeration in this instance, as in the calculation of the flow off the ground, and it was assumed to be only 16 per cent. greater than was given by the gauge at the Queen's College. The following are some of the results:—

Maximum rainfall, 1852 47·71 inches.

Mean rainfall for fourteen years, 1851

to 1864 38·42 inches.

Average of the three dry years, 1855-6-7 32·76 inches.

Minimum year's rainfall, 1855 28·80 inches.

The question still, however, remains to be answered, how much of this rainfall is available for water supply?

Twenty or thirty years ago, the evaporation was taken as proportional to the rainfall, and was variously estimated at one-sixth, one-third, and two-thirds of the mean annual rain, according to circumstances. At the present day the balance of opinion seems to be that the amount of evaporation is not proportional to the rainfall; that it is either constant, or within narrow limits, where there is an identity, or similarity, in the physical features of the

districts compared ; that it varies under different circumstances in this kingdom from 9 inches to 19 inches ; and that the estimated amount for any particular case, must be left to the experience and judgment of the Engineer.

Many of the apparent differences of opinion on this subject have arisen from a loose manner of using the word 'evaporation ;' for while it is by some intended to express the total evaporative force, with others it means 'the loss,' or difference between the rainfall and the supply, which is the resultant fact of greatest practical value. That the 'loss' cannot be constant, but will depend in a great measure upon the distribution of the rain, will be obvious from the consideration, that two years of precisely the same rainfall will give, for the same district, a very different supply, if in the one there be a wet summer, and in the other a wet winter. It will in some cases occur that there will be a gain, so to speak, instead of a loss, as in the instance before mentioned, of the months of December and January. And if there be one or two months in summer of absolutely dry weather, it is possible that the loss on the year may be less, by from 3 inches to 6 inches, than if heavy rain had fallen.

From this, and from similar considerations, the mean loss in the Woodburn district, was calculated in the following manner:—The records for the year 1864-5, showed, that for the six months from November to May, the actual loss amounted only to 0·415 inch, while from May to November it was 13·744 inches. For the first period it never exceeded $\frac{1}{2}$ an inch in a month ; for the second it varied from 1 inch to nearly 4 inches in the same time. For the three months, November, December, and January, the average loss was taken at 0·20 inch ; for February, March, and April at 0·40 inch ; for May, June, and July at 2 inches ; and for August, September, and October at 2·80 inches. The minimum flow of the streams was taken for the six winter months at 0·8 inch per month, and for the six summer months at 0·4 inch. The average monthly loss was now deducted from the rainfall of each month, as previously determined, but in all cases where the remainder did not amount to the average minimum flow, the latter quantity was inserted.¹ The results will be found in Table No. 2, page 462.

¹ The particulars of each month's supply can be consulted at the Institution.

TABLE No. 2.

Year.	Rain.			Loss.	Supply.
	Winter.	Summer.	Total.		
1851	15·76	19·98	35·74	13·94	21·80
1852	29·70	18·01	47·71	12·34	35·37
1853	20·13	19·03	39·16	12·01	27·15
1854	16·58	17·98	34·56	14·23	20·33
1855	10·91	17·89	28·80	14·23	14·57
1856	15·96	18·99	34·95	15·01	19·94
1857	22·03	12·51	34·54	11·79	22·75
1858	20·42	20·64	41·06	15·16	25·90
1859	21·68	13·33	35·01	11·86	23·15
1860	21·86	22·48	44·34	14·40	29·94
1861	17·58	21·87	39·45	13·68	25·77
1862	24·15	21·29	45·44	14·15	31·29
1863	19·12	23·72	42·84	14·38	28·46
1864	17·47	16·78	34·25	14·81	19·44
Average	19·53	18·89	38·42	13·71	24·71

Hence it appears that the loss varies in this district from 11·79 inches to 15·16 inches, the mean annual loss being 13·71 inches. The supply ranges from 14·57 inches to 35·37 inches, the mean annual supply being 24·71 inches. The years of maximum and minimum supply were also the years of maximum and minimum winter rain. It will likewise be perceived, that in the years 1856 and 1857, in which the rainfall only differed by 0·41 inch, the difference in the loss was 3·22 inches, arising from there having been a winter rainfall of 15·96 inches in the former, and of 22·03 inches in the latter year.

These conclusions, however, depend upon the correctness of two assumptions, viz., that there is a constant ratio between the rain fall near Carrickfergus and at Belfast; and that the observed monthly losses in the year 1864-5 enable the losses of the previous fourteen years to be estimated with sufficient accuracy. The method adopted does not present any results contrary to previous experience, or to such reasoning as can be applied to those results.

When the quantity and distribution of the available rain have been ascertained, the storage capacity required for the maintenance of a constant supply, amounting either to the whole, or to any part of the mean available rain, is merely a matter of arithmetical computation, and is measured by the longest period of defect of supply over demand. The particulars of the storage required for all quantities, from the mean annual supply down to that of the minimum year, have been calculated, and are given in terms of inches, days, and cubic feet per acre, in

TABLE No. 3.

Rain:— Inches.	Period on which Storage depends.	Storage.			Waste per Cent.	
		Inches.	Days.	Cubic Feet per Acre.		
24·71	78 months, May, 1853, to Nov., 1859 . . . }	29·22	431	106,000	0	Mean
24·00	78 months, ditto . . . }	24·54	373	89,000	3	..
23·00	42 months, May, 1853, to Nov., 1856 . . . }	18·04	286	66,000	7	..
22·00	42 months, ditto . . . }	15·39	255	56,000	11	..
21·00	35 months, Dec., 1853, to Nov., 1856 . . . }	11·17	194	41,000	15	..
20·00	33 months, Feb., 1854, to Nov., 1856 . . . }	9·57	175	35,000	19	..
19·00	6 months, May, 1857, to Nov. 1857 . . . }	6·98	134	25,000	23	..
18·28	6 months, ditto . . . }	6·62	132	24,000	26	Average three dry years.
17·00	6 months, ditto . . . }	5·98	129	22,000	31	
16·00	6 months, ditto . . . }	5·48	125	20,000	35	
15·00	6 months, ditto . . . }	4·98	121	18,000	39	..
14·57	6 months, ditto . . . }	4·76	119	17,000	41	Minimum year.

To store the whole quantity yielded by the Woodburn district—24·71 inches—a reservoir capable of containing 106,000 cubic feet per acre, or 431 days' supply, would be necessary. To store 18·28 inches, the average of the three dry years, the reservoir must contain 24,000 cubic feet per acre, or a supply of 132 days. While for the minimum rain, 14·57 inches, a capacity of 17,000 cubic feet per acre, or a storage of 119 days, would be sufficient. For all quantities, from the minimum up to a little above the average of the three dry years, the storage depends on the period of six months' drought; for all quantities above this, it will depend upon periods varying from two years and nine months, to six years and a half. It should be remarked, that in calculating this table, the reservoir was supposed in each case to run down to emptiness, thus giving strictly the amount of storage required. Of course, in practice a margin of safety should be added. In Plate 25, diagrams 1 to 4 show the storage worked out for each month of the fourteen years, and for quantities of 24·72 inches, 22 inches, 20 inches, and 18 inches. Diagram 5 shows the state of the reservoir for a supply of 24 inches for eleven years and of 20 inches for the three dry years. In the last example, 11·44 inches, or 174 days of a constant supply of 24 inches are required; and the case is applicable, where special demands may be restricted, whenever there is any apprehension of failure. It is worthy of remark, that although with different assumed quantities of rain the water in

[1865-66. N.S.]

store attains its minimum in different years, that minimum invariably occurs in the month of October.

From a consideration of the facts, it would appear, that, so far as regards the economical supply from the Woodburn district, it would not be prudent to attempt to store a greater quantity than about ten per cent. over the average of the three dry years, provided the extent of the gathering grounds could be increased. The maximum storage may, however, be provided in cases where natural reservoirs can be greatly increased in range at an inconsiderable expense; as at Lough Mourne, situated to the east of the Woodburn district, where a deep cut into the lake, and a short embankment of moderate height, would store the whole rain. It may be also observed, that when the supply of a town is derived from several separate streams, each having reservoirs, but all discharging eventually into the same conduit, the whole may be worked as one system, and the deficiency of storage on one stream may be supplemented by surplus storage on another, which presents more suitable sites for the construction of reservoirs.

The subject has hitherto been discussed only in relation to the economical supply of towns, but the consideration of the relative interests of the water companies and of the millowners must not be lost sight of. At first it may not be easy to perceive how injustice can arise by the purchase of water power, if, as is often the case, both the companies and the owners gain, the former by paying and the latter by receiving double its value. Yet the Engineer should never forget that his especial province is, to improve with as little incidental injury as possible. It is, therefore, clear, that he should always economize useless or injurious floods, if by pursuing that course, he can obtain his object at the same cost as by the destruction of mill-power.

The question of water power is, however, of too great importance to allow of its being treated in a satisfactory manner in the present Paper. It is one which is daily claiming more attention, and it suggests the inquiry whether the principle of economy in expenditure for providing a town supply should so far prevail, as to induce an injurious interference with the natural regimen of rivers, and the destruction by instalments of the whole water power of the country. Indications were not wanting, in the last session of Parliament, which would lead to the belief, that the Legislature would eventually greatly restrict, if not entirely prevent, such injudicious interference with rivers.

The proportion of the mean annual flow of the Woodburn river, applicable to the supply of the Woodlawn Mills, was determined from the daily gaugings already described. Those mills are the lowest on the stream except one, and receive the entire waters of both its branches, which flow from a rain basin of 4,750 acres. The water

wheel is capable of consuming, at full work, 1,400 cubic feet per minute, or 840,000 cubic feet in the working day of ten hours. Whenever, therefore, the river delivered this, or any less quantity in twenty-four hours, the whole discharge, 583 cubic feet per minute, would be consumed by the mills, provided only that the mill ponds, at and above Woodlawn, were capable of containing twelve hours' supply, so that no waste should occur during the night. Those ponds have in reality twice that capacity.

The quantity at the gauges, corresponding to a discharge of 583 cubic feet per minute at the mills, was ascertained to be 418 cubic feet per minute. All gaugings exceeding that quantity were reduced to it, and all those which were less, or equal to it, were set down at the observed amount. In this way the daily quantity of water available for the supply of the wheel was accurately ascertained, and was compared with the whole flow of the stream, as determined by observation. The following are the results:—

TABLE No. 4.

MONTHS.	Total Discharge.	Loss on Sundays and by Floods.	Available for Mills.	Per Cent.	Day's Full Work.
	Inches.	Inches.	Inches.		
July	0·36	..	0·36	100	7·35
August	0·53	0·12	0·41	78	8·44
September	2·55	1·48	1·07	42	21·91
October	2·41	1·64	0·77	32	15·78
November	3·46	2·31	1·15	33	23·49
December	2·71	1·48	1·23	45	25·13
January	3·22	2·14	1·08	34	22·09
February	2·31	1·38	0·93	40	19·00
March	2·19	1·15	1·04	48	21·32
April	0·47	..	0·47	100	9·50
May	1·10	0·50	0·60	54	12·22
June	0·40	0·02	0·38	95	7·78
	21·71	12·22	9·49	43·69	194·01

Of the total flow off the ground, 21·71 inches, there was lost on Sundays and by floods 12·22 inches, leaving 9·49 inches available for the supply of the wheel.

It must not, on this account, be concluded that 44 per cent. of the mean annual rain, is the proportion due as water compensation, nor indeed that the latter is a fixed quantity; for although it has been stated that one-third of the available rain will, in general, be an ample allowance, the quantity available for water power is dependent on so many circumstances, that each case requires its own solution. In this instance, the available quantity depends, among other things, upon the size of the wheel itself, which is capable of consuming 1·78 times the mean flow of

the stream, and economizes 43·69 per cent. of the entire water, or in other words, 194 days' full work during the year. If the capacity of the wheel were reduced to 1·5 of the flow, the wheel would work for 213 days, and the yield would be 41·17 per cent. If again reduced to 1·25 of the flow, it would work 218 days, and give 39·14 per cent.; and if it were just equal to the flow, it would work 243 days, but would only yield 30·79 per cent., of the total available rain.

These facts may be taken as quite accurate in relation to the Woodlawn Mills; but it is not desired to extend them to other cases, nor to touch the question of the absolute quantity, much less the value, of the water to which the miller is entitled. And indeed, although the habit of rough generalization, and what is called "rapid approximation," may, of late years, have been forced on the profession, and may perhaps be excused by the exigencies of Parliamentary practice, it may be doubted, whether such treatment is suited to many of the questions which arise with regard to water supply, or to that critical consideration which all subjects are certain to receive at the Meetings of this Institution. Therefore, agreeable as might be the task of generalizing facts, which have been collected and arranged at an amount of cost and labour seemingly disproportioned to their worth, the Author has refrained from undertaking it, and has given them merely as some contribution, though a small one, towards a record of exact observation.

The communication is accompanied by a series of diagrams, from which Plates 24 and 25 have been compiled, and by a daily register of the rainfall in the Woodburn district, and at Queen's College, Belfast, from June 30th, 1864, to June 30th, 1865.

FLOW OF WATER OFF THE GROUND.

PLATE 25, VOL. XXV.

Diagrams showing the quantity of Water in Store, at the end of each month, for fourteen Years ending December 31st 1864.

WOODBURN RIVERS.

Note. In the Years 1851, 59, & 64, the rainfall was below the average.
In the Years 1852, 53, 58, 60, 61, 62, & 63, the rainfall was above the average.
The four consecutive dry Years were 1854, 55, 56, & 57.

R. MANNING DEL.

Minutes of Proceedings, Institution of Civil Engineers, Vol. XXV. Session 1865-66.

Scales.
Horizontal, one inch equals one Year.
Vertical, one inch equals ten Inches.

WILL BRADLITH CASTLE ST HULBORN.

APPENDIX.

DISCHARGE of the WOODBURN RIVERS for Nine Months, from July 11, 1865,
to March 31, 1866.

MONTH.	Woodburn. Observed Flow per Minute.		Total Observed Flow per Minute.	Run off Ground.	Calculated Rain 17·6 per cent. above Queen's College.	Queen's College Rain.	Estimated Flow.
	South.	North.					
1865.				Inches.	^{sq} Inches.	Inches.	Inches.
July . . .	56	31	87	0·23	1·23	1·047	0·40
August . . .	263	188	451	1·63	3·88	3·303	1·08
September . . .	52	29	81	0·29	0·45	0·382	0·40
October . . .	673	357	1,030	3·72	5·77	4·909	2·97
November . . .	958	571	1,529	5·34	4·40	3·736	4·20
December . . .	325	201	526	1·90	3·25	2·760	3·05
1866.							
January . . .	769	488	1,257	4·54	4·15	3·523	3·95
February . . .	579	404	983	3·20	3·38	2·867	2·98
March . . .	406	347	753	2·72	4·03	3·429	3·63
				23·57	30·54	25·956	22·66

RAIN.

	Queen's College.	Woodburn.
From December 11 to December 31	1·272	1·30
January 31	3·523	4·70
February 28	2·867	3·30
March 31	3·429	3·55
	11·091	12·85
11·091 × 1·160.		12·87
11·091 × 1·176		13·04

REMARKS ON FORMULÆ FOR DISCHARGE OVER NOTCHES OR WEIRS.

All formulæ for the discharge of water depend upon the principle that the velocity is proportional to the square root of the head. This theorem was published by Torricelli in the year 1643: it is a consequence of the laws of the fall of heavy bodies, and has been verified by numerous and independent experiments. It is true, that in a solitary instance, a few years ago, doubt was cast on this principle, but without success, and Mr. Francis, the accomplished author of the Lowell experiments, has shown how any one may verify it for himself with little trouble. It may therefore be taken to be a settled principle accepted by all hydraulicians.

The mean theoretical velocity of water passing over a notch, or weir, is—

$$V = \frac{2}{3} \sqrt{2gH}.$$

The actual velocity will be less than this, and the quantity discharged will be diminished by the effects of loss of velocity, and by contraction in the passage of the water over a notch or through an orifice. As those effects will fall upon the discharge, a single co-efficient has been sought for by experiment, which is called 'the co-efficient of discharge,' by giving a mean value to which the formula for weirs has been put into the simple shape—

$$Q = 214 L \sqrt{H^3}.$$

It is evident that this co-efficient (214) cannot be constant, except Q be exactly proportional to H and L. All experiments prove that this is the case with regard to H, but not to L, and therefore M. D'Aubuisson and others have given co-efficients for different values of the latter quantity. For example, when the width of the weir is only one half that of the river channel, the co-efficient will be, not 214, but—

$$\left(214 \times \frac{.617}{.662} \right) = 199.5$$

By carefully correcting the formula by the use of the proper co-efficients, results sufficiently accurate for all practical purposes will be obtained. Still the formula is not quite correct in principle, for contraction at the ends will take place in proportion to the height over the weir, and not to its length, and therefore the formula given by Mr. Francis will be more consistent with theory. The correctness of the co-efficients, 200 and 0.1, depends, however, upon the care taken in determining them experimentally, and must be accepted, unless those co-efficients are modified by future experiments, more extended, and acknowledged to be more exact. An example will afford the means of comparing the results given by each of the two formulæ.

A weir five feet long, and one half the breadth of the river, with 6 inches of water over it, will give—

By the ordinary formula without correction :—

$$Q = 214 L \sqrt{H^3} = 214 \times 5 \sqrt{0.5^3} \quad \text{Cubic Feet per Minute.} \quad = 378.30$$

By the same, corrected for width of channel :—

$$Q = 214 \frac{.617}{.662} \times 5 \sqrt{0.5^3} \quad = 352.59$$

By the Lowell formula :—

$$Q = 200 \left(5 - (0.2 \times 0.5) \right) 0.5^{\frac{3}{2}} \quad = 352.82$$

A weir 10 feet long, the full width of the river, with

12 inches over it, would give, by the ordinary formula 2140.00

By the Lowell formula 2000.00

The velocity of approach is generally very small, and it may be observed, that the Woodburn experiments were made, not for determining a co-efficient, but for the practical purpose of gauging the flow off the ground. To increase the confidence to be placed in their correctness, the Author has made accurate measurements of the river channel behind the notch on the South Woodburn, and by this means a close approximation to the velocity has been obtained. Taking it into account, he has increased the quantities given, in the ratio

$$\left(\frac{H+h}{H} \right)^{\frac{3}{2}}$$