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"The Capacity of Storage-Reservoirs for Water-Supply."

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1. INTRODUCTION.

IN the English system for the water-supply of towns, by collecting the drainage of large catchment-basins, one of the most important problems is the determination of the capacity for storage, which should be provided in the reservoirs.

In the earlier works designed on this plan this point did not receive sufficient attention, because at that time the data required were not available. Hence reservoirs were constructed of insufficient size, causing a sensible deficiency in the water-supply in dry seasons. As the dams of the storage-reservoirs could not be raised in height without endangering their stability, new reservoirs and new gathering-grounds had to be added—a proceeding sometimes difficult and always costly.

For a long time engineers were obliged to apply the results of experience gained in existing waterworks to the design of new systems, by giving to the reservoirs a fixed capacity for a given area of gathering-ground. If, for example, in an existing system of water-supply, a storage-capacity of 2,500 cubic metres (88,288 cubic feet) was found adequate for 1,000 hectares (2,471 acres) of gathering-ground, the reservoir of a new system was designed to afford a proportionate storage-capacity. But as the amount of storage necessary depends on circumstances which vary in different localities, it is clear that in reservoirs thus designed, it is only by accident that a deficiency of water-supply, in a series of years, is prevented.

2. THE ORDINARY FORMULA.

The purpose of the storage-reservoir is to equalise the fluctuations of supply and demand during an indefinitely long period of time. The circumstances of an average year are therefore not sufficient to determine the quantity to be stored. Hence empirical rule has been adduced, based on the conditions which obtain during a period of three consecutive dry years, or years in which the rainfall is below the average.[1]

Let R be the average rainfall during three consecutive dry years estimated in millimetres, Z the number of days' storage which should be provided, then, according to this rule,[2]

$$Z = \frac{1{,}000}{0 \cdot 198 \sqrt{R}}.$$

The volume of water to be stored in one day is

$$T = B + C + V - D,$$

where B = demand of the town;
C = compensation to the stream;
V = loss by evaporation from the surface of the reservoir;
D = dry-weather flow into the reservoir.

The quantities are all estimated for a period of twenty-four hours.

According to the above formula, and in England,

$$Z = 100 \text{ to } 250 \text{ days.}$$

The formula is suitable only for English conditions, where the amount of compensation-water is regulated by law, being usually one-third to one-fourth of the available supply from the catchment-basin. The formula would not be applicable for German or Austrian localities, where the amount of compensation-water is settled by free agreement with the owners of the water-rights.

3. Empirical Method hitherto adopted.

The method most commonly adopted in deciding the capacity of a storage-reservoir is a purely empirical one, and depends on the consideration of the period of greatest drought only.

Any probable quantity is assumed for the capacity of the storage-reservoir, and it is further assumed that the reservoir is full at the beginning of the period of drought. By simple addition of the monthly supply to the reservoir during such a period, and sub-

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[1] In such periods the average annual rainfall is taken as one-sixth less than the average rainfall of a long series of years.—Editor.

[2] If R is in inches

$$Z = \frac{1{,}000}{\sqrt{R}}.$$

traction of the supply to the town, and for compensation, also estimated for successive months, a calculation is made of the quantity in the reservoir at the end of each month for a period of a year. Should the calculation show a deficiency (the volume in the reservoir appearing as a negative quantity), the capacity originally assumed for the reservoir is increased, and the calculation is repeated.

The proceeding is an imperfect one, and is also laborious. The calculation may be shortened by assuming, as the capacity of the reservoir, the sum of all the deficiencies during the drought instead of any empirical quantity, and then making the detailed calculation for the period of a year.

But this method of calculation is open to the objection that it is only in certain cases that the capacity of the reservoir arrived at is sufficient to equalise the fluctuation of supply and demand, not only during a single drought, but during a series of periods in which the supply is deficient.

The records of the rainfall at Vienna prove this assertion. The least rainfall, and consequently the least available supply to the reservoir, generally occurs in the winter months. Thus for December, January and February, the standard rainfall is at the rate of 111 millimetres (4·44 inches). The driest winter was that of 1857–58, when for these months the rainfall was 42 millimetres (1·68 inch). In calculating the capacity of the reservoirs for the water-supply to West Vienna, this winter was taken as the basis of the calculation by the technical experts, and the empirical calculation for the driest year (1858) was made by the method explained above.

But the graphical method of the Author applied to this case, and embracing a period of thirty-seven years, during which records of rainfall were available, showed that both in the dry period, 1858–59, and in that of 1855–56, a greater storage capacity was required than in the period 1857–58. Further, the true measure of the storage required was found to be that necessary to equalise the supply and demand during the period extending from May 1855 to May 1856, as it was during that period that the greatest deficiency for the whole period of thirty-seven years was found to occur.

4. New Graphical Method of Calculation.

The following is an outline of the Author's method of determining the capacity required for storage, to equalise the supply and demand during any period for which rainfall observations are available.

First the supply to the reservoir and the outflow are estimated for successive equal periods of time, usually one month, and for the whole period of time to be considered. The successive intervals of time are set off along an axis of abscissas, to any convenient scale, and the estimated inflow to and outflow from the reservoir in each interval are set up as ordinates. Connecting the points thus found two curves (or broken lines) are obtained, which may be denominated briefly as the supply-curve and the demand-curve.

The form of the supply-curve *a a*, Plate 5, Fig. 1, or curve, the ordinates of which represent the available supply to the reservoir, will in general be similar to the rainfall-curve.

The demand-curve will have a form similar to the curve *b b*. It will be the same every year, if the compensation-water is taken entirely from the reservoir. If, however, the compensation-water is partly supplied from streams which do not flow into the reservoir, as in the case of the West Vienna project, then the quantity of compensation-water from the reservoir, and consequently the whole outflow from the reservoir will vary, increasing as the rainfall decreases, and *vice versâ.*

The difference between the two ordinates at each month's end represents either a surplus (positive) or deficiency (negative), according as the ordinate of the supply-curve is greater or less than the ordinate of the demand-curve. These surpluses and deficiencies for each month are measured and entered in a Table as follows:

Column 1 gives the periods for which the successive surpluses or deficiencies are estimated.

Column 2 the surpluses or positive differences of the ordinates.

Column 3 the deficiencies or negative differences of the ordinates.

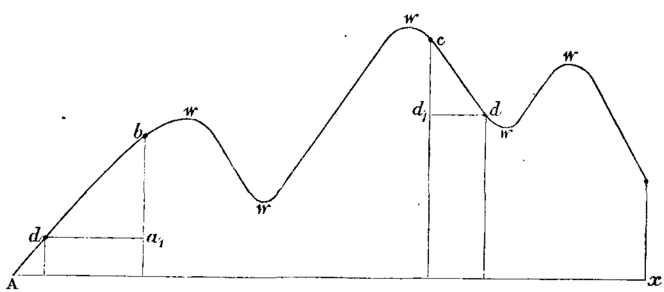
Column 4 contains, opposite each date, the algebraic sum of the numbers in columns 2 and 3 up to that date.

The following Table gives the numbers thus obtained from the diagram, Plate 5, Fig. 1.

Next, the numbers in column 4 are set off on a diagram as ordinates, the abscisses being the intervals of time as before (Fig. 2). The foot point of each ordinate is the end of the corresponding absciss, representing the period of time estimated from the point of time at which the calculations begin. By joining the ends of the ordinates a curve is obtained, which will be denominated the mass-curve.

1			2	3	4
			Differences.		Algebraic Sum or Ordinate of Mass-Curve.
			Surplus. +	Deficiency. −	
1854	End of	December		..	0
1855	,,	January	1,048,877	..	+1,048,877
,,	,,	February	697,030	..	1,745,907
,,	,,	March	..	989,153	756,754
,,	,,	April	..	671,962	84,792
,,	,,	May	5,330,640	..	4,415,432
,,	,,	June	5,006,492	..	9,421,924
,,	,,	July	..	197,561	9,224,363
,,	,,	August	4,246,729	..	13,471,092
,,	,,	September	1,426,470	..	14,897,562
,,	,,	October	..	377,643	14,519,919
,,	,,	November	1,621,640	.	16,141,559
,,	,,	December	..	397,039	15,744,520
1856	,,	January	828,979	..	16,573,499
,,	,,	February	833,518	..	17,407,017
,,	,,	March	..	1,368,287	16,038,730
,,	,,	April	..	2,651,043	13,387,687
,,	,,	May	395,225	..	13,702,912
,,	,,	June	1,548,786	..	15,331,698

Fig. 2.



The mass-curve has the following properties:—

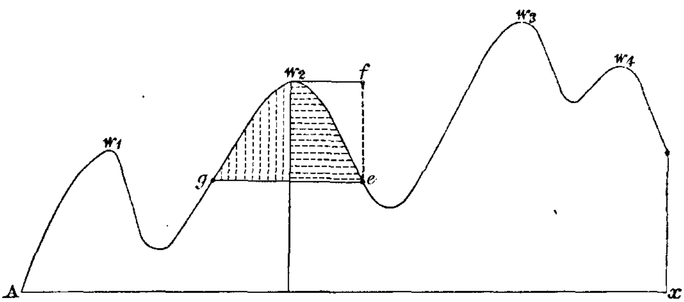
1. For the interval of time between any two points on the axis of abscisses, the difference of the corresponding ordinates is the surplus, if positive, or deficiency, if negative, during that interval. An ascending part of the curve therefore marks a period during which the quantity in the reservoir is increasing and a descending part of the curve a period during which the quantity in the reservoir is diminishing.

The crests and hollows, *w*, of the curve indicate those instants of time at which the supply and demand are equal.

2. If a horizontal line is drawn forwards at a crest, for example,

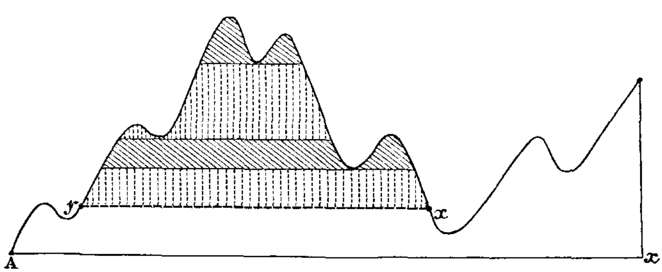
the line $w_2 f$ at w_2 (Fig. 3), the distance $e\ f$ of a point e on the descending part of the curve, from the horizontal line, represents the total deficiency within the period represented by $w_2 f$. To cover this deficiency there must have been previously an equal storage, and $e\ f$ therefore represents the amount of storage required to meet the deficiency in the period $w_2 f$.

FIG. 3.



3. From what previous point of time the storage to meet the deficiency must have commenced is found, by drawing the horizontal line $e\ g$, backwards from e, till it meets an ascending part of the curve. In the period represented by $g\ e$ the supply and demand are equal. Hence $g\ e$ may be termed a balancing line. This is true of any point such as x, Fig. 4, on a descending part of the curve,

FIG. 4.



that is the supply and demand are equal for the period represented by the balancing line $x\ y$, all the subordinate deficiencies being balanced by corresponding surpluses, as is indicated by the shading of the diagram.

4. In the mass-curve certain hollows t_1, t_2, t_3 . . . . (Plate 5, Fig. 5) may be selected. Lines drawn through these points mark off periods within which the surplus during one part of each

period must be stored to balance the deficiency in another part of the period.

5. The quantity of water represented by the vertical projections Y_1, Y_2, Y_3 ..... of the remaining portions of the ascending curve, between the lines, flows away or at all events is not required to meet the demand during the period of time considered.

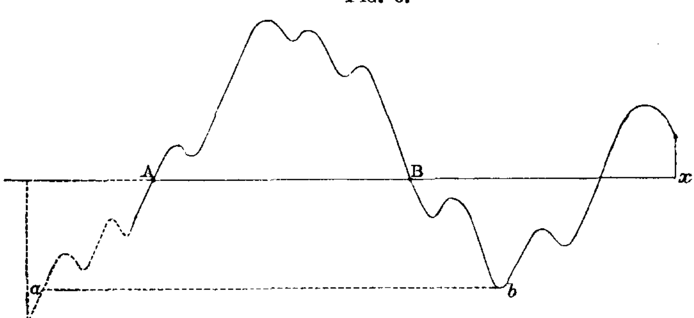
6. The vertical distances J_1, J_2, J_3 ..... between the lowest and highest crests and hollows in each period are the storage-capacities required to equalise the fluctuations of supply and demand during those periods.

7. Balancing quantity J. The greatest possible vertical distance J, between a crest and hollow for any one period represents the capacity of the storage-reservoir which is sought for. For if the storage-reservoir is capable of equalising the supply and demand during the period in which J is greatest, it is sufficient in all other periods.

8. The period in which this greatest value of J occurs is therefore the critical period. In the case shown in Fig. 5, the critical period is that represented by t^1, t_1; during that period all the surplus of supply over demand during parts of the period must be stored to meet the deficiency in the remainder of the period.

9. The ordinates of the mass-curve will be positive (drawn upwards) so long as the sum of the surpluses is greater than the sum of the deficiencies up to the point of time considered. When the mass-curve crosses the axis of abscisses the whole previous surplus is exhausted, and if it falls below the axis of abscisses, it is necessary to carry back the curve to some earlier point of time

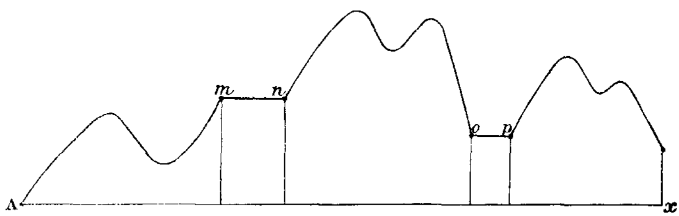
FIG. 6.



than that at which it was first started. Thus, for example, suppose the curve had been drawn from A (Fig. 6), and had been observed to fall below the axis of abscisses beyond B, then it would be necessary to prolong the curve backwards from A to *a* to make a complete investigation of the period within which the points A and B occur possible, since they fall within a period the balancing line of which is *a b*. In other words the mass-curve will remain above the axis of abscisses so long as the total supply estimated from the beginning of the time considered exceeds the total demand, and only falls below it if the demand exceeds the supply.

10. The mass-curve becomes a straight line parallel to the axis of abscisses for any periods such as *m n*, *o p* (Fig. 7), during which the supply and demand are exactly equal. Such cases, however, occur rarely in practice.

Fig. 7.



It is clear from what has been said that a single period of drought does not afford a safe basis for determining the proper storage capacity of a reservoir. That storage-capacity can only be determined with safety, by examining a series of such periods. Hence also, it is not the year in which the least total rainfall occurs which gives the measure of the storage-capacity required, but the period in which the greatest fluctuation of supply and demand happens. The limitation of the time considered to a year is erroneous in principle, because the year is in reference to the question to be solved an unessential condition. The essential intervals of time are the periods during which the supply and demand are balanced.

Plate 5, Fig. 8, represents part of a mass-curve based on observations of the rainfall in the district of the Wiener Wald, and comprises those portions of the curve only which required to be taken into detailed consideration. The curve was drawn on the method described above, and by examining it, it will be seen that a storage capacity of 4,019,330 cubic metres is required, to equalise the greatest fluctuation of supply and demand during a period extending from the end of 1854 to the end of 1859. It will be seen also that it is not in the driest year, 1858, that the greatest fluctuation occurred, but in a period extending from the end of August 1855 to the end of April 1856. It is this period, therefore, which is the critical period, and which determines the capacity required for storage.

The Paper is accompanied by several diagrams, from which Plate 5 and the woodcuts in the text have been prepared.

STORAGE RESERVOIRS.

Fig : 1.

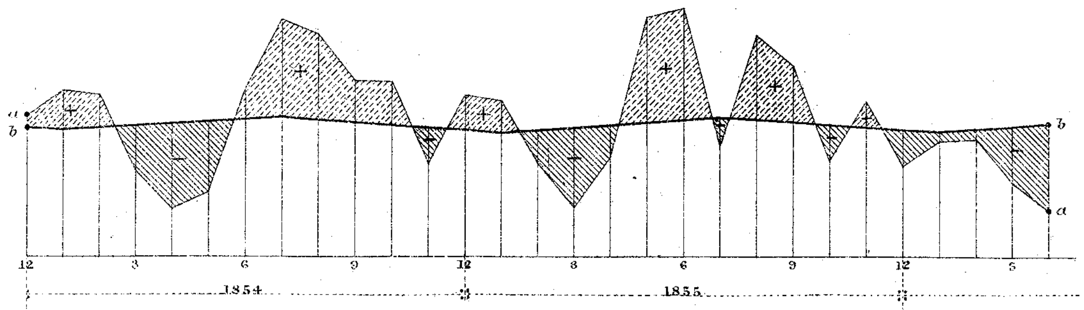


Fig : 5.

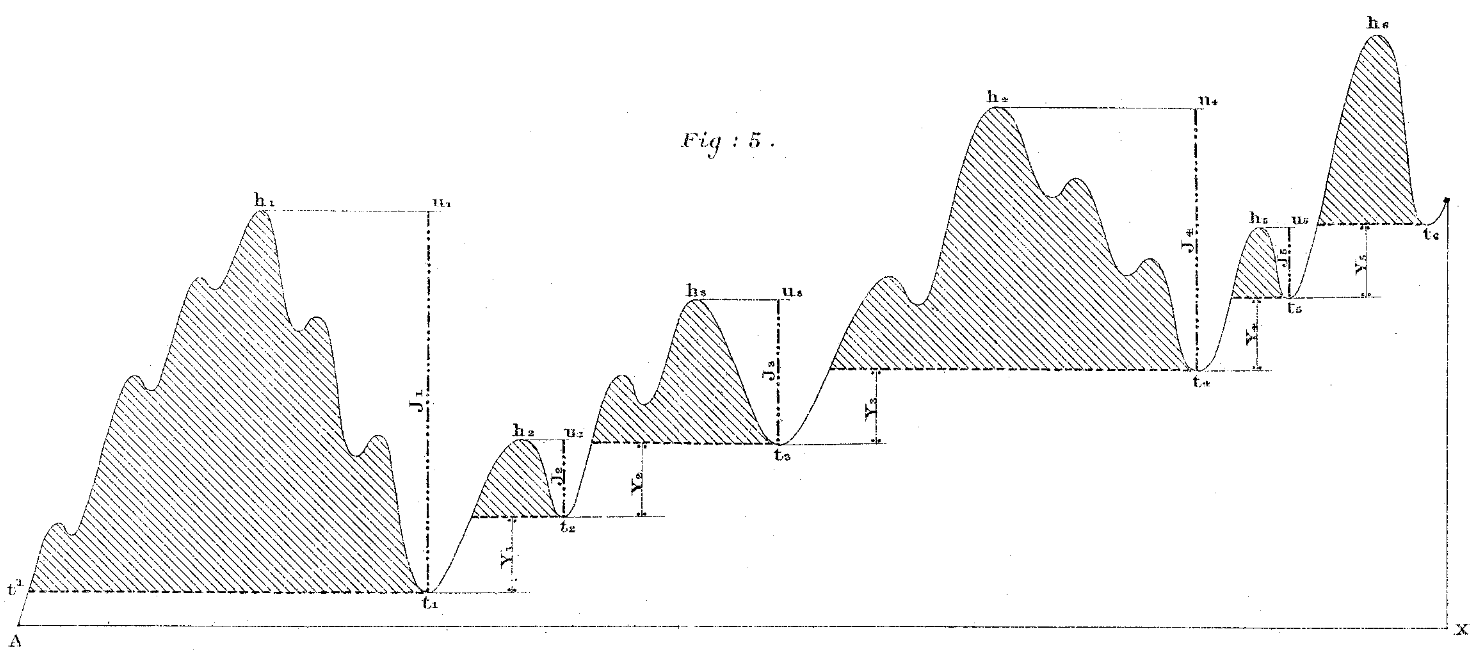
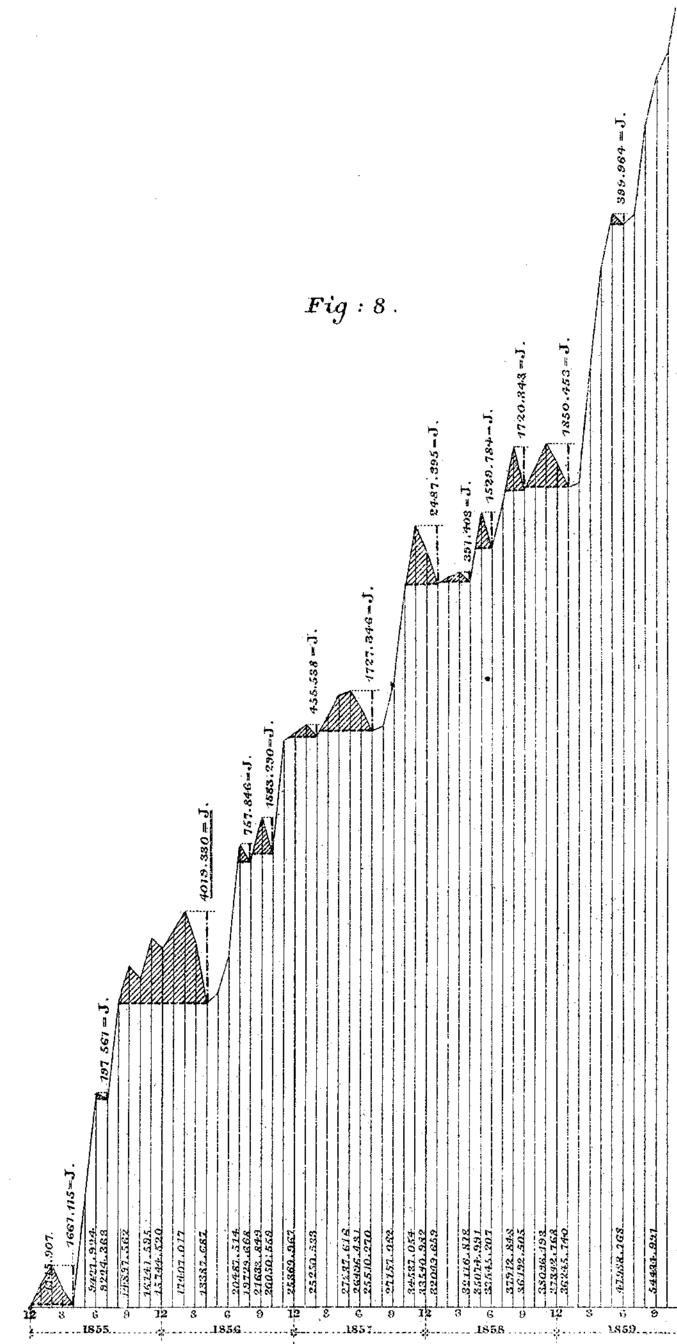


Fig : 8.



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