Rainfall and Juvenile Water as the Feeding Origins of the Hot Springs in Beppu

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Abstract

In the city of Beppu there are about a thousand hot springs. With regard to about a hundred of them, our Laboratory has observed the discharge rate and temperature once a week for more than ten years. Comparing the results thus obtained with the results of meteorological observation, we have tried to elucidate the feeding origin of the spring water. This is indeed the purpose of this paper.

First, analysing the annual variation we showed that the causes of the variation in spring discharge bear the following ratio:

Rainfall: Variation of atmospheric pressure: Fluctuation of sea level $=5:2:1$;

and those of the variation in spring temperature bear the following ratio:

Variation of air temperature: Change of cooling effect due to the discharge variation $=2:3$.

It was also found that the secular variation in discharge is chiefly caused by the difference of precipitation except for a gradual decrease on account of the deposition of incrustation in the underground conduit pipes or the erosional break of the pipes causing leakage.

Then, comparing the total discharge of all Beppu hot springs with the annual precipitation on the whole catchment area, we pointed out that most of the percolating rain becomes hot water. Moreover we ascertained that the effect of rain appears most remarkably in the same month but thenceforward it decreases according to the exponential law in time, and its after effect remains about three years.

Finally, touching on the juvenile water in the Beppu spring water, we inferred that it would be about a half of the whole amount.

The discharge rate of certain hot springs in Beppu suddenly increases with copious rain and decreases during drought. The nearer a hot spring is to the Bluff, the more marked this phenomenon becomes. Hence, undoubtedly a large amount of the hot spring water depends upon the supply of rain water.

In the present paper, with the object of elucidating the feeding origins of the hot springs, the annual and secular variation of the Beppu hot springs and their causes are first investigated and analysed quantitatively; and then the abundance of discharge of these springs is ascertained by comparing the total annual discharge of all the hot springs

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* T. Nomitsu has changed the spelling of his name to "Nomitu."

in the city with the annual precipitation on the catchment area ; and finally, consideration is given to the origins of the hot spring water, the available period of the after effect of rainfall, and the percentage of juvenile water in the hot spring water. Various other interesting problems on the relation between the hot springs and precipitation, such as local differences in the influence of rainfall and the time taken by the rainfall to begin to show its influence, will be dealt with in other papers.

I. The annual change of discharge rate and its causes

1) *Data* :—The successive observations of the Beppu hot springs have been carried out since April 1925, once a week on a number of welling mouths, though unfortunately the observation was suspended from March 1931, to January 1932, because of circumstances at the Beppu Laboratory. Furthermore, the springs or the number observed varied somewhat year by year as in Table I, and some springs were dredged or re-dug by their owners, so that not all the results obtained from the observations can be accepted as they stand.

Table 1. Springs utilised for the investigation of annual variation.

Year	1925, Apr. - 1927, Mar.	1927, June ~ 1928, May	1928, June ~ 1929, May	1929, June ~ 1930, May	1932, Feb. ~ 1933 Jan.	1933, Feb. ~ 1934, Jan.	1934, Feb. ~ 1935 Jan.
	4 343 544 868	31 343 692	4 820	4 671	4	58	4
	17 357 561 910	58 357 751	31 1040	31 771	58	130	58
	62 370 564 992	92 409 771	58 1153	58 801	87	343	87
	69 383 666 996	110 418 820	130 1291	87 1291	130	472	130
	92 409 675 1153	120 451,1 935	343	130	343	671	343
Spring	100 430 692	130 472 996	418	343	418	1040	418
No.	130 451,1 771	147 506 1040	472	418	472	1153	472
	173 506 781	173 530 1045	530	472	530		564
	233 511 820	189 542 1050	542	530	542		634
	243 526 823	233 564 1153	571	542	580		813
	258 530 838	240 646 1280	671	564	671		1153
	279 534 854	263 671 1283	771	571	801		1260
	291 539 861	291 685 1291	801	580	1153		
Total Number	44	39	17	17	13	7	12

Therefore, selecting 193 welling mouths which had been observed just for a year without suspension of observation or re-digging, the monthly mean discharge-rate covering eight years was determined as shown in Table 2 and graphically in Fig. 1.

Table 2. Sum of the flow-rate (in litre/min.) of the observed springs, and the average.

Month / Year	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III	Number of Springs
1925	473.60	496.76	511.08	522 59	506.96	583 81	552.93	534.07	511.33	487.53	483 91	484.15	44
1926	448.84	447.65	458 22	452.40	441.84	471.35	445.54	425.76	428.81	412.82	377.00	399 39	44
1927			490 62	495.64	507.10	541.23	532.71	499.81	472.62	463 08	447.96	446.19	39
1928	435 42	432 34	215.65	226.64	238.61	241.54	230.16	229.22	214.85	206.18	202.65	193.76	17
1929	185 97	187.52	220.14	257.70	249.06	246.03	248.54	240.88	233.81	226.71	207.36	209.04	17
1930	197.24	201.63											17
1931											148.08	130.24	13
1932	124.32	120.41	147.28	169.53	166.09	166.07	165.64	155 28	149.64	135.67	60.10	58.01	13
1933	55.89	56.34	56.17	54.88	54.37	53 00	55 40	55.63	50.26	51.30	150 37	149 51	7
1934	143 08	141.36	133.43	132.69	127.78	142.24	141.17	148.31	142.77	141.52			12
Number of spr.	193	193	193	193	193	193	193	193	193	193	193	193	193
mean	**10.70**	**10.80**	**11.57**	**11.93**	**11.87**	**12.67**	**12.29**	**11.86**	**11.42**	**11.01**	**10.76**	**10.73**	

What are the *causes of the annual variation in the rate of discharge* of the Beppu hot springs? What is the *relative weight* of these causes? The following are generally regarded as influencing the welling discharge of the hot springs :—

(I) Internal causes :

(1) Variation in the amount of juvenile water.

(2) Variation in the underground water-path (variation in the water vein, clogging or enlarging of rising pipes, etc.)

(II) External causes :

(3) Variation in amount of the percolating water (precipitation)

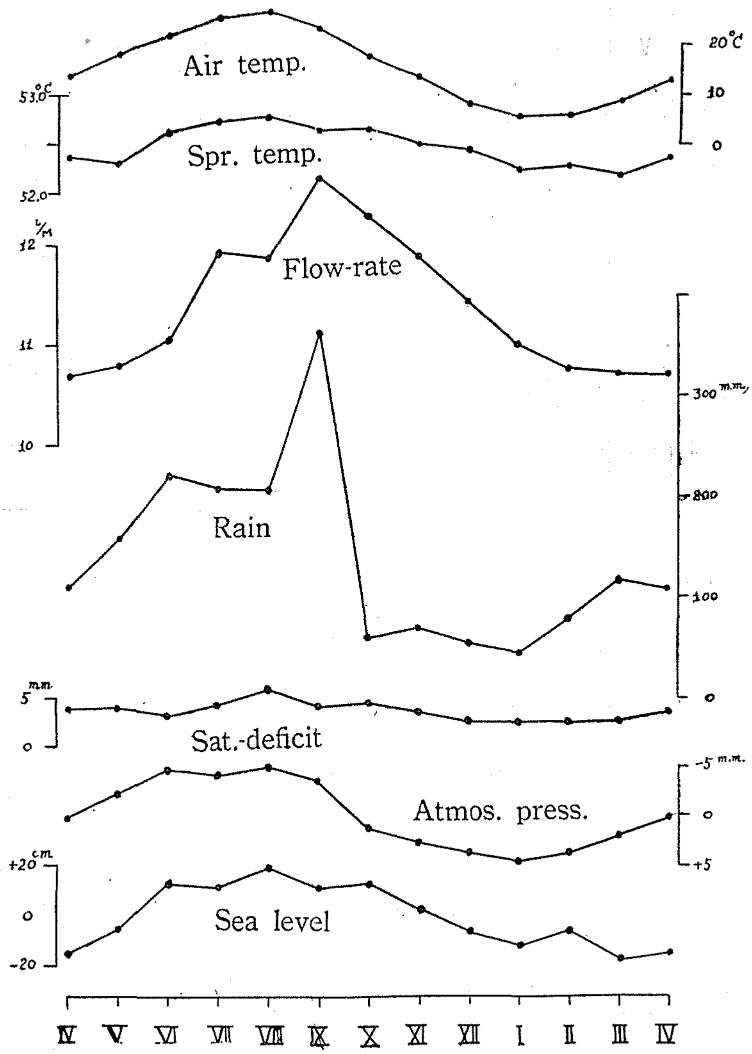
(4) Variation in the amount of condensed water (humidity or saturation deficit)

(5) Influence of atmospheric pressure.

(6) Influence of the tide.

The internal causes (I), connected with earthquakes, explosion of volcanos, or other accidents, may be neglected as far as the seasonal variation for a short period is concerned, though very important to the secular variation. (5) and (6) in (II) serve merely as controlling valves for the welling of the hot spring, and have no essential influence on the amount of spring water. Only (3) and (4) have any essential influence on the water quantity of hot springs. The condensed water, (4), means the watery vapour in the atmosphere which has been cooled

Fig. 1. Annual variation of the flow-rate and temperature of the Beppu Springs with meteorological elements.



and condensed in voids in the ground. It has been emphasized by North European scholars as one of the origins of the common ground water. It may be true for such a cold district of little rain as North Europe, but in a volcanic and hot spring zone of high subterranean temperature such as Beppu and especially in the case of excessive precipitation, there can be no objection to disregarding the possible condensed water, which at greatest must be very little compared with the percolation of rain water. We have of course investigated the saturation deficit, and the result agreed with our expectation. Thus it is undoubted that the rain is the most important external element as a feeding origin of the Beppu hot springs and that the seasonal variation in the precipitation is a chief factor in the variation of the rate of discharge of the springs. However, the annual variation in the spring discharge shown in Table 2 and Fig. 1 is to be interpreted with consideration not only of the influence of precipitation, but also of the effects of the atmospheric pressure and tide which control the welling discharge. We will, therefore, analyse the annual variation in the spring discharge under the three heads of precipitation, atmospheric pressure and tide, and discover the ratio among them.

For this purpose we must know the annual variation in precipitation, atmospheric pressure, and tide. Table 3 indicates these fundamental data. Their graphs are drawn in Fig. 1.

Table 3. Annual variation of meteorological elements and sea level.

Month	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III	Mean
Rain (mm.)	**103.1**	**154.8**	**220.5**	**209.8**	**206.8**	**360.5**	**58.5**	**69.5**	**53.5**	**43.9**	**78.0**	**116.3**	137.0
Bar. press. (+700 mm.)	**55.1**	**52.9**	**50.3**	**51.1**	**50.2**	**51.6**	**56.3**	**57.8**	58.7	**59.5**	**58.8**	**56.9**	754.9
Sat. defic. (mm.)	3.1	4.2	3.1	4.2	5.7	4.0	4.4	3.5	2.4	2.4	2.5	2.9	3.5
Sea level (cm)	**117**	**126**	**145**	**143**	**151**	**143**	**145**	**134**	**125**	**120**	**126**	**114**	132
Water density σ_t	24.83	24.54	24.50	24.29	23.85	22.68	24.59	24.77	24.89	24.84	24.79	24.96	24.46

It is to be noted here that the annual variations in meteorological elements, such as precipitation or atmospheric pressure, must be the average of observations made during the years with due account taken of the number of springs observed those years. The values given in Table 3 were obtained in this way from the annual meteorological reports covering ten years, issued by our Beppu Laboratory. As to the annual variation in the sea level only, there was no datum available covering many years except the tide-gauge record made in 1932 by the Construction Office of Ôita Harbour and arranged by the Hydrographical Department of the Navy; and we adopted this. As to the specific gravity of the sea water, the values which the Fisheries Experimental Station of Ôita Prefecture observed in Beppu Bay in 1932 were used. These data seem somewhat insufficient. But fortunately the fluctuation of monthly mean sea level is only between 30～40 cm., although the daily tidal-range extends to 2 m. Accordingly it is expected that the annual variation in the mean sea level little influences the spring discharge. Therefore, even the data obtained from one year's observation will not be inappropriate.

It is due to the variation in the submarine hydraulic pressure that the rise and fall of the sea level influence the spring discharge, but the whole of the seasonal fluctuation of the sea level does not cause variation in the submarine pressure. Therefore, it will be convenient now to determine the effective part of the fluctuation of mean sea level which causes variation in the submarine pressure. According to studies previously made by one of the present authors (Nomitu)[1], the annual variation in the mean sea level can be considered to be balanced statically by the specific gravity of the sea water, the atmospheric pressure, etc. Consequently, in the case where the sea is over several hundred metres in depth and both the temperature and salinity of the water in the depths of the sea show scarcely any annual variation, the submarine pressure does not vary, although the height of the sea level varies seasonally. But in the case of a shallow sea, where the specific gravity of the sea water varies down to the bottom, the submarine pressure varies in accordance with the specific gravity of the sea water. As Beppu Bay has a depth of 70 m. at the deepest and its mean depth from the coast is 35 m, the annual variation in the water temperature extends to the bottom, so that the submarine pressure will of course show annual variation. To determine this variation, subtract from the observed fluctuation of the sea level the rise and fall caused by both the specific gravity of the sea water σ_t (0, 20, 40, 60 m mean) and by the atmospheric pressure. Table 4 shows the calculation of the effective fluctuation of sea level from the actual variation of sea level, specific gravity of the sea water, and atmospheric pressure. Here,

influence of the specific gravity on the sea level $= -\dfrac{\sigma_t}{1000} \times 3500$ cm,
influence of the atmospheric pressure p on the sea level $= -\Delta p \times 13.2$ cm.,
and the mean depth is taken as 35 m.

2) *The effects of the atmospheric pressure and the sea level on*

1. T. Nomitsu: The causes of the annual variation of the mean sea level along the Japanese coast; These Memoirs, **10** (1927), 125.

Table 4. Effective part of the annual variation of mean sea-level acting as the submarine pressure.

		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
(i)	Deviation of sea level	cm −12	−6	−18	−15	−6	13	11	19	11	13	2	−7
(ii)	$\Delta\sigma_t$	0.38	0.33	0.50	0.37	0.08	0.04	−0.17	−0.61	−1.78	0.13	0.31	0.43
(iii)	Its effect on sea level	cm −1	−1	−2	−1	0	0	1	2	6	0	−1	−2
(iv)	Barom. effect on sea level	cm −6	−5	−3	0	−3	6	5	6	4	−2	−4	−7
(v)	(iii)+(iv)	cm −7	−6	−5	−1	−3	6	6	8	10	−2	−5	−9
(vi)	(i)−(v)	cm **−5**	**0**	**−13**	**−14**	**−3**	**7**	**5**	**11**	**1**	**15**	**7**	**2**

the spring discharge :—Now the annual variation in the discharge of the Beppu hot springs will be analysed and the effects of the different causes will be examined.

As stated in the previous paper[1], the atmospheric pressure influences the spring discharge by increasing or decreasing the controlling pressure at the upper end of the welling mouth of the hot springs. When the atmospheric pressure grows higher, the spring discharge decreases; when it becomes lower, the discharge increases. By investigating 7 hot spring mouths of Beppu, the barometric coefficient c was found to be, as a mean,

Barometric coefficient, $c = 8.6\ \mathrm{min}^{-1}$ ....(i)

Concerning the *tidal coefficient* h for the influence of the sea water pressure on the discharge of the Beppu hot springs, we have reported in the previous paper a considerably large number of values derived from investigation of the daily tidal influence. Their mean value is as follows;

The increase in the discharge-rate per 1 cm. rise of the sea level=
$h = 0.024$ litre/min. ....(ii)

These coefficients for the atmospheric pressure and the tide are truly significant as showing the general facts, but they cannot be considered applicable directly to the whole city of Beppu, for they would surely give excessive results. Because the hot springs, whose coef-

1. The Beppu Hot springs and the Tide, with the Effect of the Atmospheric Pressure; These Memoirs, **22** (1939), 403.

ficients of atmospheric pressure and tide we could determine, were those which had these influences to a remarkable degree and which could be investigated separately. As many hot springs are only slightly and indistinctly influenced by them and their coefficients cannot be determined, it is presumed that the mean coefficient of all the hot springs in the city is definitely smaller than the above mentioned values and is probably not more than half of them. Now, what would be practically a mean coefficient for the whole city? We devised the following means to determine it.

For two years from April 1925 to May 1927, the observations on 44 springs were most satisfactorily continued. We sorted the statistics of the discharge of these springs according to the distance of the springs from the coast by every 100 m, as shown in Fig. 2. From this figure it is evident that the influence of the precipitation is large at a distance from the coast and becomes smaller with the approach to the coast. Noticing this fact, we sorted the statistics mentioned above, of the mean annual variation for 10 years by the distance from the coast, and obtained Fig. 3, which also indicates that the effect of the rain is small on the coast and large on the Bluff.

Assuming that the coefficients of the tide ($h=0.024$) and the atmospheric pressure ($c=8.6$) derived from the above mentioned few hot springs might be directly applied to the whole city, the annual variation in discharge influenced by both the atmospheric pressure and tide was calculated. The result is shown by the dotted lines in Fig. 3. The figure shows that the welling mouths which are more than 600~700 m. from the coast are most remarkably influenced by the rainfall, and, therefore, the influences of the atmospheric pressure and the tide cannot be directly seen. But, in the case of less than 500~600 m., the parallelism between the observed variation and the calculated influences of the atmospheric pressure and the tide is distinct. It must be noted here that, though they are parallel, the values calculated (the dotted lines) are always larger than the actual. Averaging all the cases from 0~100 m. to 500~600 m, the ratio becomes:

$$\text{Observed value/Calculated value}=0.54.$$

Namely it denotes that the coefficients of the atmospheric pressure and the tide for the whole city are 0.54 (about a half) of (i) & (ii), the mean value for a few hot springs already obtained. This is concerning the combined effect of tide and atmospheric pressure. As it is not known in what ratio each of them must be subtracted, both ratios have necessarily been assumed to be 0.54 respectively.

Fig. 2. Relation between the variation of spring discharge and the distance from the coast.

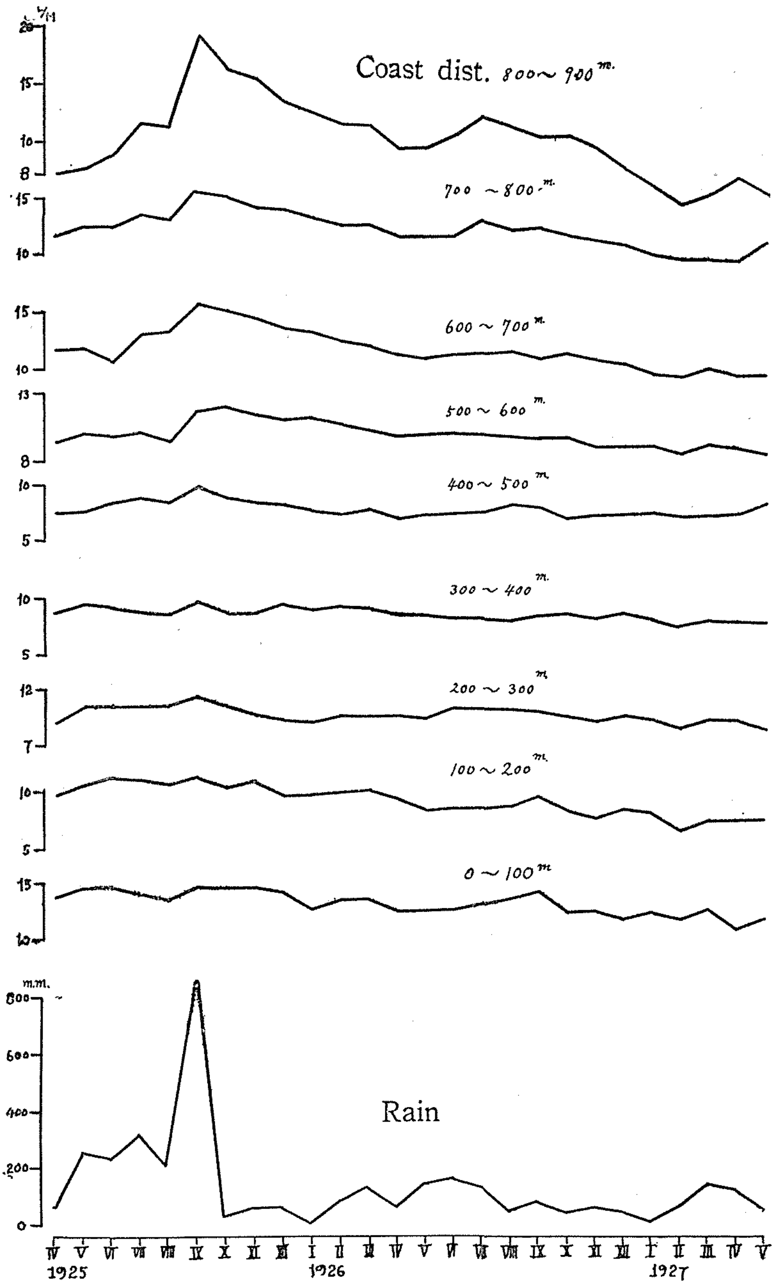
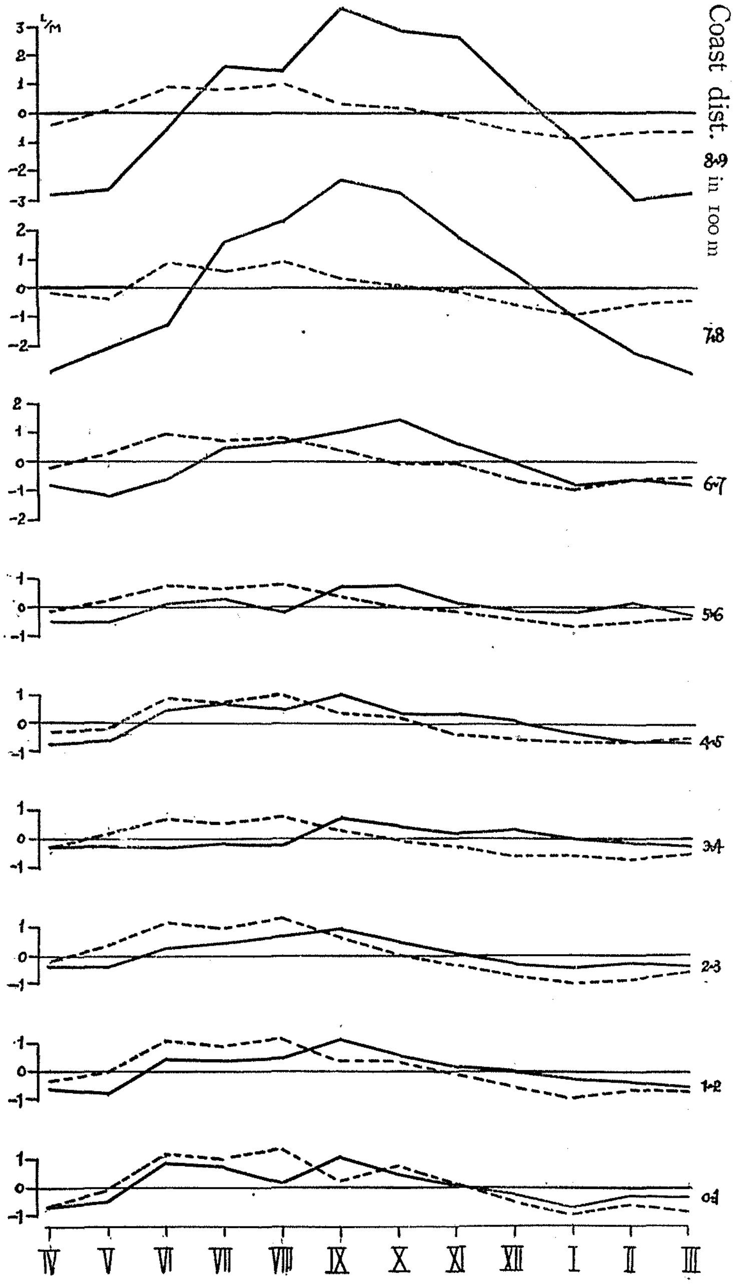


Fig. 3. 10 years mean annual variation of the discharge and the calculated effect of both sea level and barometric pressure (dotted lines), classified by the coastal distance



Thus the mean value of the coefficients of the atmospheric pressure and the tide for the whole city could be approximated. It is easy to measure the variation caused by the atmospheric pressure and tide in the mean annual variation in all the Beppu hot springs. Multiplying the deflection of the atmospheric pressure, shown in Table 3, by the coefficient of the atmospheric pressure, and also the annual variation in the effective sea level by the coefficient of the tide, we have Tables 5 & 6, which show the effect of the atmospheric pressure and the sea level respectively.

Table 5. Annual variation of discharge-rate (litre/min.) due to the barometric change

Month	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III
Deviation of air-pressure (mm).	0.2	−2.0	−4.6	−3.8	−4.7	−3 3	−1.4	2.9	3 8	4.6	3.9	2.0
Its effect on sp. flow (L/M)	−0.02	+0.18	+0.41	+0.34	+0.42	+0.30	+0.13	−0.26	−0.34	−0.41	−0.35	−0.18

Table 6. Fluctuation of the discharge rate (litre/min) due to the annual variation of mean sea-level.

Month	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III
Effective change of sea-level (cm)	−14	−3	7	5	11	1	15	7	−2	−5	0	−13
Its effect on sp. flow (L/M)	−0.17	−0.12	+0.08	+0.05	+0.10	+0.08	+0.22	+0.10	+0.01	−0.07	−0.01	−0.16

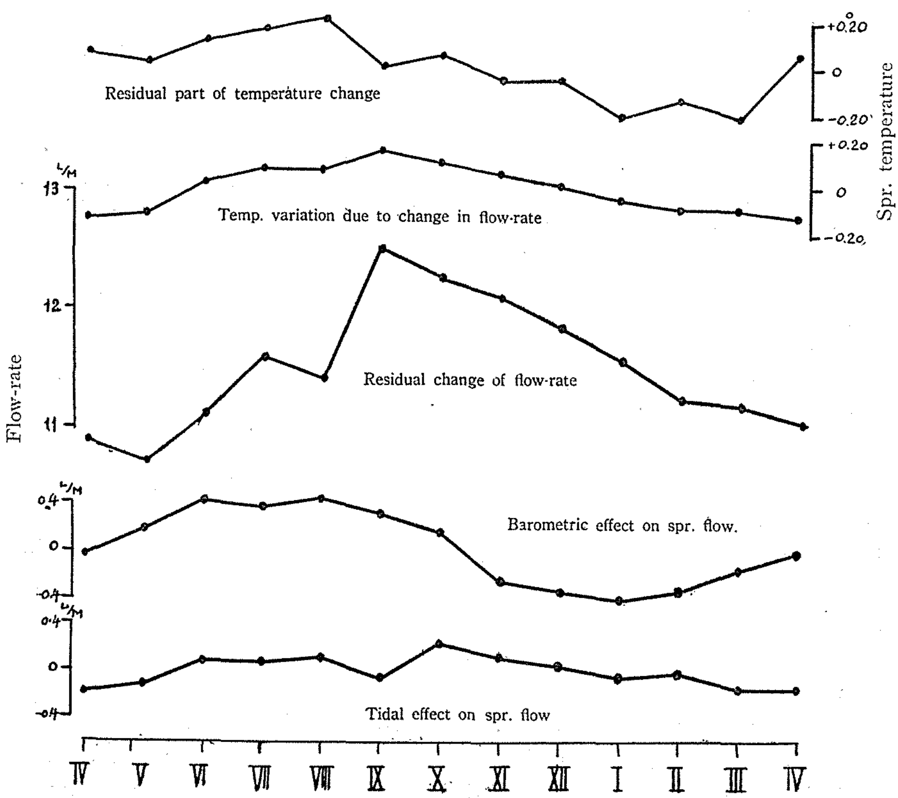
3) *The effect of the precipitation on the spring discharge*:— Subtract the above stated effects of both atmospheric pressure and sea level from the total annual variation in the welling discharge, and the remainder may be regarded as the direct effect of precipitation, as shown in Table 7.

The above mentioned results can be presented as in Fig. 4. In this remaining discharge the effect of natural depletion and of condensed water may be included as well as that of precipitation. But after a glance at the tendency of the annual variation of the saturation deficit and of the variation of the spring discharge shown in Fig. 1, we scarcely feel it necessary to take the condensed water into account. In other words, it is not what German scholars call the Berlin type, but rather the Paris type. There was distinctly recognized a close relation between the remainder of the spring discharge and the annual variation of precipitation. Though the curve itself has a few points showing un-

Table 7. Effect of rain on the spring discharge (litre/min)

Month	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III
Total rate of flow	10.70	10.80	11.57	11.93	11.87	12.67	12.29	11.86	11.42	11.01	10.76	10.73
Barometric effect	−0.02	+0.18	+0.41	+0.34	+0.42	+0.30	−0.13	−0.26	−0.34	−0.41	−0.35	−0.18
Tidal effect	−0.17	−0.12	+0.08	+0.05	+0.10	−0.08	+0.22	+0.10	+0.01	−0.07	−0.01	−0.16
Residue (rain-effect)	**10.89**	**10.74**	**11.08**	**11.54**	**11.35**	**12.45**	**12.20**	**12.02**	**11.75**	**11.49**	**11.12**	**11.07**

Fig. 4. Analysis of the mean annual variation in discharge and temperature.



parallel variations, this is not strange because the after effect of rain remains for several months. The spring discharge which is the minimum in May, begins to increase suddenly in June on account of the rainy season. In July the precipitation, though somewhat decreasing, is much more than the annual mean, and so the spring discharge continues to increase, being influenced by the after effect of the rainy season. As the rainfall becomes less in August, the spring discharge decreases somewhat. In September, the typhoon period, we frequently have heavy rains, and the spring discharge grows larger with the precipitation and reaches the maximum of the year. Thereafter till January the precipitation is strikingly scanty, but on account of the after effect of abundant rain from the rainy season to the typhoon period, the spring discharge keeps its predominance though gradually diminishing. The months from January to April, in which the precipitation somewhat increases, are still within the dry period whose monthly amount of rain is far less than the mean of the year, and consequently the spring discharge still has a tendency to decrease. It reaches its minimum in May. Furthermore, every minute variation in the monthly precipitation can be traced by comparison with the variation in the spring discharge. If a month of deficient rain occurs during the period of increasing spring discharge, the increase is promptly restrained; if it rains during a dry period in which the spring discharge is decreasing, the decrease is relieved.

In short, it has been shown that *the annual variation in the discharge of the Beppu hot springs depends upon the three causes—precipitation, atmospheric pressure, and sea level.* From the amplitude ratio shown in Table 7, we know the *relative importance of the three causes* to be roughly as follows:

Sea level: *Atmos. pressure*: *Rainfall*$=0.39:0.83:1.71 \fallingdotseq$ **1 : 2 : 5**

These three causes act in making the spring discharge abundant in summer and scanty in winter, but the actual discharge is remarkable in late summer and autumn owing to the after effect of the precipitation, the phase thus rather lagging. The after effect of the precipitation will be stated minutely later.

II. The annual variation in the spring temperature and its causes

Concerning the annual variation in the spring temperature as well as in the amount of the discharge, the 193 welling mouths observed for 10 successive years were averaged and Table 8 was obtained.

Table 8. Statistics of spring temperature (°C)

Month / Year	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III	Number of Springs
1925	2340.5	2344.1	2344.9	2349.0	2351.5	2352.2	2347.3	2338.8	2334.3	2328.3	2325.6	2322.9	44
1926	2324.4	2326.1	2326.7	2329.9	2328.4	2323.3	2319.5	2309.0	2314.6	2300.1	2293.4	2288.1	44
1927			2056.5	2060.1	2059.6	2052.9	2050.5	2040.3	2032.1	2026.4	2019.5	2020.9	39
1928	2017.7	2015.2	878.3	877.8	876.3	875.5	886.2	888.4	885.7	883.1	881.4	877.5	17
1929	876.1	876.5	896.0	902.4	901.9	900.0	899.6	899.8	898.2	895.1	893.3	891.2	17
1930	887.1	888.9											17
1931											695.5	694.0	13
1932	691.4	683.3	688.9	689.2	688.1	685.8	687.0	684.9	684.1	682.7	353.3	353.1	13
1933	356.2	352.4	351.5	348.5	355.7	353.4	352.8	351.2	350.5	352.7	628.3	627.3	7
1934	624.8	622.6	617.3	615.6	616.8	616.5	617.7	619.2	619.5	614.7			12
Number of springs	193	193	193	193	193	193	193	193	193	193	193	193	193
Mean	**52.42**	**52.38**	**52.63**	**52.71**	**52.74**	**52.64**	**52.65**	**52.50**	**52.43**	**52.24**	**52.28**	**52.20**	**52.49**

Incidentally the mean atmospheric temperature similarly calculated is shown in Table 9, shown graphically with the spring temperature in Fig. 1.

Table 9. Mean annual variation of the air temperature at Beppu (°C)

Month	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III	Mean
Air temp.	12.7	17.4	20.6	25.1	26.0	22.6	17.1	13.0	7.9	5.4	5.6	8.2	15.1

As a *cause of the variation in the spring temperature*, the *atmospheric temperature* (with the surface ground temperature) is first considered. The atmospheric and spring temperature-curves, shown in Fig. 1, certainly indicate a close relation between them. But certain points cannot be explained by this alone. The spring temperature and the air temperature are both at the maximum in August, and at the minimum in April, which is also the month when the discharge rate is at the minimum. Also, the spring temperature rises suddenly in early summer and falls gradually in autumn. Thus the general tendency in temperature approximates the variation in the rate of discharge. When the discharge rate increases with rainfall, the temperature also becomes higher, Thus the *variation of discharge rate is obviously the second cause* of the annual variation in the spring temperature.

In another paper[1] we have investigated and ascertained that the spring temperature certainly varies also with a short period variation in discharge rate accompanying the daily tide. Accordingly we may say that all of the causes which influence the rate of discharge seem to be connected with the variation in spring temperature. But they all act indirectly. Therefore, the discharge rate which acts directly may be taken to represent them. Then, how does the rate of discharge influence the spring temperature? As stated in the cited paper, in the case of Beppu, the hot water is cooled while it rises through the conduit pipe. The larger the rate of discharge is, the shorter will be the time the water remains in the pipes, and hence the less it will cool; and consequently the higher the spring temperature becomes. The loss of temperature is to be reckoned as follows:

$$T_b - T_u = \frac{2\pi r l}{q} \overline{k\frac{\partial T}{\partial r}} \qquad \text{(iii)}$$

where, T_b, T_u: the temperature at the lower and the upper end of the vertical flowing pipe respectively,

$2r$: dia. of pipe, l: length of pipe, q: discharge rate,

k: thermal conductivity of the earth,

$\partial T/\partial r$: mean temperature gradient at the pipe-wall side.

Examining the effect of the tide on 16 mouths of the Beppu hot springs, we obtained the following mean value of $k\frac{\partial T}{\partial r}$:

$$\overline{k\frac{\partial T}{\partial r}} = 0.213 \quad \text{calorie cm. min.}$$

Though it may be improper to apply this value derived from only a few springs to the case of all springs, we adopt it for the present. From 193 springs whose temperature were measured, the means of $2r$ and l were as follows;

$$2r = 4.31 \text{ cm.,} \quad l = 5705 \text{ cm.}$$

Substituting these values in (iii), the annual variation in the spring temperature due to the cooling in the conduit pipe is obtained as given in Table 10. Their graphs are drawn in Fig. 4, top. The variation of the spring temperature subtracted the effect of the change of discharge rate, as would be expected, keeps symmetry having the centre in August and runs parallel with the variation in the air temperature. How does the air temperature influence the spring temperature?

1. loc. cit. p. 47.

Table 10. Analysis of the mean annual variation in temperature of 193 springs during 10 years.

Month	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III
Deviation of obs. temp.	−0.07	−0.11	0.14	0.22	0.25	0.15	0.16	0.01	−0.06	−0.25	−0.21	−0.29
Effect of flow-change	−0.13	−0.12	0.03	0.07	0.06	0.15	0.11	0.06	0.01	−0.04	−0.08	−0.08
Residue	+0.05	+0.01	0.11	0.15	0.19	0.00	0.05	−0.05	−0.05	−0.21	−0.13	−0.21

It is chiefly because of the fact that the heat escaping to the air in the neighbourhood of the welling mouth and to the surface earth is different in summer and winter.

Since the annual variation in the Beppu hot springs is only $0^\circ.4$ in amplitude and parallel to the discharge rate, the effect of mixing superficial ground water of temperature nearly equal to the atmospheric temperature may be disregarded in the discussion of the present problem. Though some springs of incomplete structure were accidentally observed, in time of heavy rain, to drop their temperature, showing that the cold rain water was mixing with the spring, yet in most springs in Beppu such effects are scarcely discernible.

We have thus attributed the annual variation in the hot spring temperature in Beppu to the effect of the atmospheric temperature and the cooling through the conduit pipe. Their relative importance is as follows ;

Discharge effect : *Air temperature effect* $= 0.28 : 0.40 \doteqdot 2 : 3$

III. The annual total discharge in all the Beppu hot springs and its feeding

Concerning the total spring discharge in Beppu, our Geophysical Laboratory measured simultaneously all the welling mouths in 1924 and 1933, and obtained the results shown in the following table.

Date	Number of active springs	Total discharge per day
1924, Sep.∼Oct.	826	16.32×10^3 (m^3)
1933, July∼Aug.	756	18.79×10^3

In 1933 the number of the spring mouths had rather decreased, but the total discharge had somewhat increased. There was in general little difference between the two results.

When we want to derive the total amount for a year from this table, the annual variation must be taken into account as stated in the previous section. In 1924 the observations were not made continuously and in 1933 also the springs continuously observed were few. Accordingly, regarding the mean annual variation given at the bottom of Table 2 as their annual variation, we have the total spring discharge for a year (assuming that a month has 30.50 and 30.42 days on the average) as follows:

$$\textit{In } 1924, \quad 16.32\times10^3\times30.50\times\frac{2\times136.97}{12.67+12.29}=5.461\times10^6\ m^3$$

$$\textit{In } 1933, \quad 18.79\times10^3\times30.42\times\frac{2\times136.97}{11.93+11.87}=6.579\times10^6\ m^3.$$

Averaging these, the *annual amount* is found to be **6.020** million m^3.

On the other hand, the origins that feed the Beppu hot springs are internally, juvenile water, and externally, precipitation. The feeding rain area may be the part which is enclosed within a water-shed line (dotted) on the map, Fig. 5, made by the Land Surveying Department, as follows:

$$\text{Water-shed area for Beppu springs}=23.07\times10^6\ m^2.$$

The precipitation in 1933 was somewhat less than the mean obtained from the observation for 10 years by the Beppu Laboratory, its annual amount being 1506 mm. In 1924, though not observed by the Laboratory, according to Ôita Meteorological Station, it was 1631 mm., being more than in the average year. The ratio of the yearly precipitation of Ôita to Beppu is 1 : 1.10 in the average. From the precipitation in Ôita in 1924, we infer the precipitation on Beppu in the same year to be 1794 mm. Thus the mean precipitation in Beppu in 1924 and 1933 may be regarded as 1650 mm. a year. Therefore, we obtain

total annual precipitation on the whole catchment area

$$=1.650\times23.07\times10^6\ m^3=38.1\times10^6\ m^3$$

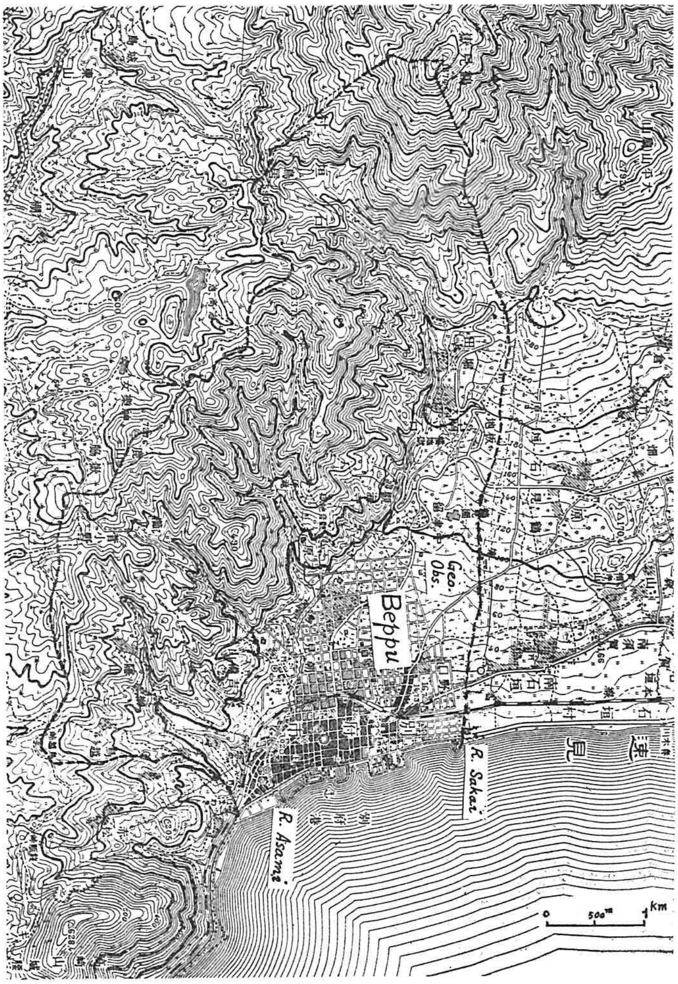
Accordingly the ratio of the total discharge of the Beppu hot springs to the total annual precipitation on the catchment area is as follows:

$$\frac{\textit{Total annual spring-flow}}{\textit{Total annual precipitation}}=\frac{6.02\times10^6}{38.1\times10^6}=\mathbf{0.16}$$

Inside the city of Beppu alone, the discharge of hot water amounts to 16% of the precipitation on the whole catchment area, east of Mt. Turumi-dake. What a startling fact this is! Besides, that hot spring

Fig. 5. Catchment-area for the Beppu hot springs.

——→N



water is flowing up from the sea-bottom is quite evident from the fact that there are natural sand-baths on a part of the shore and many hot springs even on the reclaimed ground along the shore, whose total discharge is large. Still more, within the same catchment area there are many hot springs which we have not yet surveyed, such as Horita, Hatiman, Kwankai-Zi, Sira-yu, and Otohara etc. If they are taken into the calculation, the total increases perhaps to 20% of the total precipitation, to 30, 40, or who can tell, to what per cent?

Rain water is, in general, disposed of in three ways—by percolation, evaporation, and run-off; and the percolated rain water becomes an origin feeding ordinary ground water or hot springs. The amount of percolating water, though varying according to the character or slope of ground, as does that of the other two, is supposed to be roughly 1/3 of the whole. As known from the topography of Beppu, most part of the catchment area forms steep hillsides, and so the surface run-off of rain water is so swift that the percolation is inferred to be relatively little. Being rather flat, the streets of Beppu make a somewhat hard slope with the difference of a height 30 m. per km. distance on the average and the houses are built there. Therefore it is thought that it may be harder for the rain water to percolate there than on the hillsides. Though the character of the ground seems to be favourable for percolation because it is made of volcanic ash, it can scarcely be believed that the amount of percolating water reaches 1/3 of the precipitation in spite of such topography. Thus it is certain that *most of the percolating amount of the rain falling on the catchment area of Beppu becomes hot spring water.* Moreover, there seems a considerable amount of juvenile water of magmatic origin there, and it is supposed to amount to many percent of the spring discharge.

In the city of Beppu, it is, in fact, generally hot water that can be obtained by digging, it being rather difficult to get cold water. The citizens use hot water for everything except cooking. Before the city water was laid, cold water had been appreciated rather than hot water. It is, however, not wholly impossible to get cold water. Cold water wells in the area from the coast to the 40 m. contour line, and also, at ebb-tide, at Matoga-hama, on the northern coast. From this evidence it is known that some of the percolating rain water does not become the origin of hot springs. Its total amount has not yet been measured, and we intend to make a study of it. When such an amount of cold water is subtracted from the amount of the percolating rain water, the percolating water alone is too little to be thought the feeding origin of all the Beppu hot springs. Therefore, we must recognize the *existence of a large amount of juvenile water.*

IV. Secular variation of flow-rate and precipitation

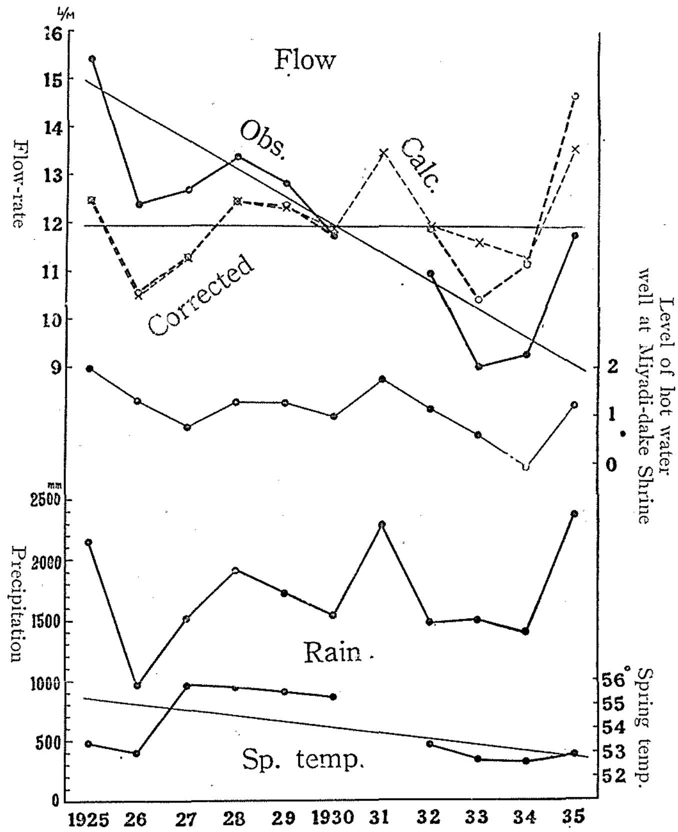
The annual mean of *spring discharge* varies, as a rule, with the year; that is, a secular variation is seen. As its causes we may recognize all the internal and external causes mentioned in Chapter 1. Of these the atmospheric pressure and sea level act too little to need to be taken into account. For the difference of the yearly mean atmospheric pressure is generally very small, that is, the difference between the maximum and minimum for the observed 10 years is only 0.8 mm,, being only 8% of 10 mm., the seasonal variation in the atmospheric pressure. With regard to the rise and fall of sea level, the difference between daily ebb and flood is 2 m. and the range of the seasonal variation covers about 40 cm., but the difference of the yearly mean sea level is less than a few cm., not being more 1/10 of the seasonal variation. Consequently the atmospheric pressure and the sea level act for the secular variation in the hot springs at least 1/10 less than for the seasonal variation. As this is within the surveying error, it can be neglected. Thus the effective causes for the secular variation of springs are change in the amount of the juvenile water and in the spring-water path as internal causes, and the variation in the precipitation as the external one.

Now concerning the secular variation in the Beppu hot springs, only 8 springs have been observed for 10 successive years, and 4 of these were dredged during the period. Therefore the data obtained are insufficient for minute discussion. For a general study, the secular variations of the 8 springs and the precipitation in each year are shown in Fig. 6.

It is at once seen from this figure that both the spring discharge and the temperature show a tendency of gradual decrease year by year. This phenomenon is related to the circumstance that the artificial hot springs in Beppu need to be dredged about every 10 years. The chief cause of this lies in the fact that the conduit pipes corrode and allow leakage, and that the incrustation is deposited in conduit pipes and clogs them by degrees. A few examples are illustrated on Fig. 9. Is the variation in the amount of the juvenile water included here? We have now no datum for judging. But even though the Beppu hot springs may show an inclination to real decay after hundreds or thousands of year, we believe such symptoms are not to be found in a single decade. As one of the evidences, we adduce the fact that the discharge of all the Beppu hot springs had increased in 1933 over that in 1924.

Next, the effect of precipitation is certainly noticed in the secular variation. From the remainder or the revised discharge got by subtracting the tendency of gradual decrease from the observed discharge shown in Fig. 6, it is recognized that in a year of abundant precipi-

Fig. 6. Mean secular variation of the 8 springs in Beppu, compared with the precipitation.



tation the spring discharge correspondingly increases and in a year of scanty precipitation it decreases.

Finally, the *secular variation in the hot spring temperature* generally follows the welling discharge, being related to it positively. As explained in the item of the annual variation, this is caused by the fact that the time of the passage through the conduit pipe and accordingly the degree of cooling varies with increase or decrease in the discharge rate. However, the influence of the atmospheric temperature on the hot spring temperature can be neglected. For the yearly mean atmospheric temperature remains through years at about 15°, and the difference between the maximum and the minimum for the observed 10 years is only 0°.8. Since the difference of 20° in the air temperature between summer and winter gives only about 0°.5 amplitude to the annual variation in the hot spring temperature, it is certain that the effect of the yearly difference in the air temperature, which is below 1/20 of the former, is quite negligible.

V. After effect of rain and inference of the juvenile water

A heavy rain suddenly increases the spring discharge not only in that month, but also in the following; two months, or even several months later, it causes much increase even if there is no additional rain. We call it the *after effect of rain*, which will be dealt with again in this chapter.

According to more than 10 years' observation made by the Beppu Laboratory, in September 1925, as if by God's peculiar grace, there was a period of record-breaking torrential rain, when precipitation for the month amounted to 858.2 mm. In the following month it was only 30 mm., which may be called, in comparison with the preceding month, no rain at all. Thereafter till the next January it rained little. This was a most favourable opportunity for studying the effect of rain, and especially its after effect. Fig. 7 shows the precipitation and the spring

Fig. 7. After-effect of the heavy rain in Sep., 1925.

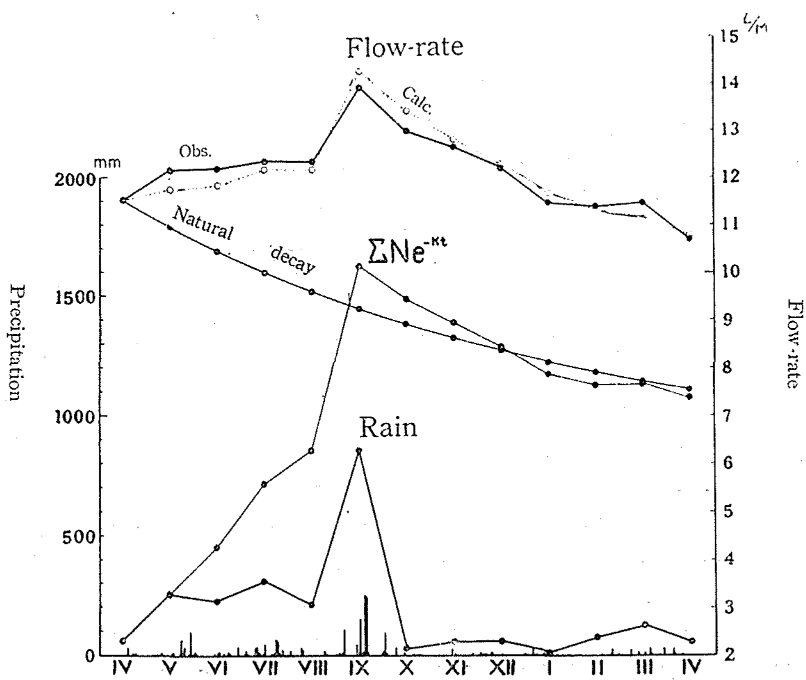


Table 11. Precipitation and flow-rate per 1 spring from March 1925 to March 1926.

Month	1925 IV	V	VI	VII	VIII	IX	X	XI	XII	1926 I	II	III	IV
Flow-rate (L/M)	11.51	12.14	12.17	12.32	12.31	13.90	12.97	12.62	12.18	11.46	11.38	11.45	10.69
Rain (mm)	58.4	253.9	228.0	310.9	210.9	858.2	28.6	52.6	58.4	9.0	76.3	124.4	56.5

discharge on that occasion, and Table 11 shows their values. Concerning the precipitation, the daily amount is denoted with vertical lines beside the monthly one. Remember that the 'rain in September' means the rainfall on the 1st, 4th, and 5th day of the month. As is clear from the figure, the heavy rain caused the spring discharge in that month to increase at a jump, and for the following two months it kept the discharge over the mean in spite of little rainfall. Its after effect generally shows an exponential tendency. If a day or an hour is taken as unit of time, the effect of rain of course does not appear immediately after the rainfall, but a few hours later the discharge starts to increase; some hours later still it reaches its maximum, and then gradually decreases. When a month is taken as a unit as in this section, from the examples shown in Fig. 7, the effect of rain may be, without a big error, put as follows:

$$F=aNe^{-kt}=F_0e^{-kt} \qquad (1)$$

where, N=monthly precipitation, t=time after rain in month,

F_0, F=discharge rates due to the rain at that month and after t month

a=coefficient of rain effect,

k=depletion index of rain effect.

This is theoretically reasonable, for it means that the decrease of water-head on the upper stream in the catchment area is assumed to be proportional to the amount of discharge. The coefficient a and k are as yet unknown. We will first deduct the value of k from the inclination of gradual decrease shown in Fig. 7. As the rain in October 1925 was much less than the heavy rain in September, the decrease in the discharge rate from September to October was to be very next to a natural diminution. And, as the rain in January 1926 was absolutely little, amounting to only 9 mm., the decrease in the spring discharge from December 1925, to January 1926, was also almost a natural diminution. From these two parts which may be regarded as the natutal diminution, we will decide the value of the depletion index k.

Suppose a month of no rain and let Q_2 represent the spring discharge in the month and Q_1 for that in the preceding month. In the case of hot springs, there is usually juvenile water J which is not influenced by the effect of precipitation, and so F in (1) is only a part of the observed discharge Q. Regarding J as invariable, from (1) we have

$$(Q_2-J)/(Q_1-J)=e^{-k}. \qquad (2)$$

If we have another occasion like this and take Q_1' and Q_2' as the whole spring discharge for the two months, we have;

$$(Q_2'-J)/(Q_1'-J)=e^{-k}. \qquad (3)$$

From (2) and (3), we can obtain the amount of J and k, that is;

$$J=\frac{Q_1Q_2'-Q_2Q_1'}{(Q_1-Q_2)-(Q_1'-Q_2')} \qquad (4)$$

$$k=\log_e(Q_1-J)-\log_e(Q_2-J)=\log_e(Q_1'-J)-\log_e(Q_2'-J). \qquad (5)$$

Only from the observed discharge, Q_1, Q_2, Q_1', and Q_2', both the natural depletion index and the juvenile discharge are easily obtained.

Now, concerning the Beppu hot springs, let the discharges in October and January be represented by Q_2 and Q_2' respectively, then from (4) and (5), or from the intersection of the (J, e^{-k}) curves obtained according to (2) and (3), we have;

$$J=6.29 \text{ litre/min}, \qquad k=0.13.$$

These values, however, must be corrected, for actually both October and January had more or less rain. For example, if there were no rain in October, the spring discharge of the month would be considered to decrease by about 0.1 lit/min. from the tendency shown in Fig. 7. Revising, moreover, the influences of the atmospheric pressure, tide, etc., we obtain;

$$J=\mathbf{6.1} \text{ litre/min.}, \qquad k=\mathbf{0.11} \text{ month}^{-1},$$

which we adopt in the later discussion.

The juvenile water 6.1 lit/min. indeed, corresponds to as much as 50.5% of 12.08 litre/min., the mean discharge in that year. If $k=0.11$, the effect of the rain decreases with the month, as indicated in Table 12. In 1 year, the effect falls to about 27% of the effect in the month when it rained; in 2 years, 7.1%; even in 3 years, 1.9%; but in 4 years, it becomes only 0.5%. Thus the effect of rain remains for 3 years, but in the 4th year it is negligible.

With the value of k thus derived, we will examine whether or not the mean annual variation in the discharge of the Beppu hot springs can be quantitatively explained by the annual variation in precipitation.

Table 12. Decay of rain-effect on the Beppu springs.

t (Month)	1	2	3	4	5	6	7	8	9	10	11	12	24	36	48	60
e^{-kt}	.896	.803	.719	.644	.577	.517	.463	.415	.372	.333	.298	.267	.071	.019	.005	.001

1) *Study on the seasonal variation in 1925*:—Since our Beppu Laboratory of the Kyôtô Imperial University began to make consecutive investigation of the spring discharge from April 1925, the discharge in April of that year, 11.51 litre/min., is taken as a starting point. It includes the effect of the rain in March and earliar, the effect of the rain in April, and the juvenile water. If there had been no rain throughout the year after the May, the spring discharge thence would be obtained by adding the invariable juvenile water to the water of rain origin which decreases from $11.51-6.1=5.41$ litre/min. at the rate given in Table 12. The values thus obtained are tabulated in Table 13.

Table 13. Supposed discharge (litre/min) if no rain after May, and that due to the precipitation after May.

Month		IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III	IV	
Supposed flow	Rain-origin $(Q-J)$	5.41	4.85	4.34	3.89	3.48	3 12	2.80	2 51	2.25	2.01	1.80	1.61	1.44	
	+Juvenile (Q)	11.51	10.95	10.44	9.99	9.58	9.22	8.90	8.61	8.35	8.11	7.90	7.71	7.54	Total
Effect of rain after May		—	1.19	1.73	2.33	2.73	4.68	4.07	4.01	3.83	3.35	3.48	3.74	3.15	38.29

The difference between the observed discharge and this discharge corresponds to the effect of the rain falling after May, which is shown in the lowest row in Table 13. In short, it corresponds to $a\sum Ne^{-kt}$ which is to be obtained by applying eq. (1) to each monthly rain and summing the values arrived at. Though the coefficient a of the effect of rain is still unknown, only $\sum Ne^{-kt}$ can be calculated as given in Table 14, for k is known. As the products of multiplying the values in the lowest row of this table by a correspond to the effect of rain shown in the lowest row in Table 13, a can be obtained by dividing the latter by the former. It may be one of the ways to calculate a for each month, and to take their mean, but here we will simply find a from the ratio of the yearly total:

Table 14. Ne^{-kt} after May, 1925.

Month	1925 V	VI	VII	VIII	IX	X	XI	XII	1926 I	II	III	IV	
Ne^{-kt}	253.9	227.3	204.0	182.7	163.4	146.5	131.3	117.7	105.3	94.5	84.5	75.6	
		228.0	204.4	183.3	164.0	146.8	131.6	118.0	105.7	94.7	84.9	76.0	
			310.7	278.5	249.7	223.6	200.3	179.5	160.6	144.1	129.0	115.7	
				210.9	189.7	170.0	152.3	135.4	122.1	109.5	98.2	87.9	
					858.2	770.0	690.0	608.0	552.7	495.5	440.0	398.0	
						28.6	25.8	23.2	20.7	18.6	16.6	14.9	
							52.6	47.2	42.3	37.8	33.9	30.4	
								58.4	52.3	46.9	41.9	37.6	
									9.0	8.1	7.2	6.5	
										76.3	68.4	61.4	
											124.4	111.6	
												56.5	Total
$\sum Ne^{-kt}$	253.9	455.3	719.1	855.4	1625.0	1485.5	1383.9	1287.4	1170.7	1126.0	1129.2	1072.1	12563.5

$$a = \frac{38.29}{12563.5} = 0.00302$$

Multiplying $\sum Ne^{-kt}$ in the lowest row in Table 14 by this a, we have the rain effect in each month, and adding it to the 2nd row in Table 13 (i. e. the supposed discharge in the case of no rain) we can obtain the monthly total discharge. Table 15 gives the results obtained. The

Table 15. Calculated values of rain-effect and the total flow-rate. (in lit/min.)

Month	1925 IV	V	VI	VII	VIII	IX	X	XI	XII	1926 I	II	III	IV
Effect of rain after May	—	0.77	1.37	2.17	2.58	4.91	4.49	4.18	3.89	3.54	3.40	3.42	3.24
Calc. flow-rate	11.51	11.72	11.81	12.16	12.16	14.23	13.39	12.79	12.24	11.65	11.30	11.13	10.78

dotted line in Fig. 7 illustrates this calculated discharge which agrees satisfactorily with the observed discharge. Little difference between them would be caused by the influences of tide or atmospheric pressure, or by the error brought about by the fact that it did not always rain in the middle of a month, but it sometimes rained at the beginning or at the end of the month.

2) *Study on the mean annual variation for 10 successive years* :— We will next study whether or not the mean annual variation (the

remaining discharge after the effects of tide and atmospheric pressure have been subtracted) of the 193 welling mouths, already mentioned in § I, observed for 10 successive years, can be explained by the mean annual variation (Table 3 with the weight) of the precipitation for these years. As it is the mean annual variation for 10 successive years, both the rain and the spring discharge caused by the rain may be regarded as being in a semi-steady state. Suppose that the rain which varies annually in the above mentioned way falls on a place where there is merely the juvenile water and thenceforth it continues to rain every year in the same way. We will calculate the spring discharge caused by the rain after 1, 2,... to limitless years. In this case, if only k is known, we have a way of calculating the value even if both J and a are not known. Assuming the value of k to be $k=0.11$ as we found it in 1925, in order to know the ratio of the effect of rain, we got Table 16 and Fig. 8 by calculating $\sum Ne^{-kt}$. The calculation of the 1st year is equal to that shown in Table 14, and since the 2nd year, we obtain the values by adding the value of each month in the 1st year to what is got by multiplying e^{-kt} to the values of the last month (March) of the previous row. In the semi-steady state after many years, the limiting value for the last month (March) is to be corresponding to the sum of an infinite geometrical progression whose first term is 867.4, the value of the last month (March) in the 1st year, and whose common ratio is e^{-12k} (the rate of decrease in every whole year). That is,

$$867.4\left\{1+e^{-12k}+(e^{-12k})^2+(e^{-12k})^3+\ldots\ldots+e^{-\infty}\right\}=867.4\times\frac{1}{1-e^{-12k}}$$

$$=867.4\times\frac{1}{1-0.267}=1183.4$$

The value of each month may be regarded as that of the following year, so that it can be obtained by adding the value of the 1st year and the product of 1183.4 to e^{-kt} in Table 12.

$\sum Ne^{-kt}$ in such a stationary stage, being multiplied by a, will be the part of rain origin included in the total discharge observed, and, therefore, a can be obtained from the ratio of the variable parts of $\sum Ne^{-kt}$ and the observed discharge. From the ratio of both amplitudes (or ratio of the sums of the absolute value of the deflection from the mean in each month) we have a:

$$a=\frac{12.45-10.74}{1603.8-1164.7}=\frac{1.71}{439.1}=0.00390.$$

Multiplying this value by the annual mean of $\sum Ne^{-kt}$ in the steady

Table 16. ΣNe^{-kt}

	Month	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III
1st year	Ne^{-kt}	118.3	106.0	95.0	85.1	76.2	67.7	61.2	54.8	49.1	44.0	39.4	35.3
			108.4	97.1	87.0	77.9	69.8	62.5	56.0	50.2	45.0	40.3	36.1
				220.0	197.1	176.7	158.2	141.7	126.9	113.7	101.9	91.3	81.8
					211.0	189.1	169.4	151.7	135.9	121.7	109.1	97.7	87.6
						184.0	164.9	147.8	132.3	118.5	106.2	95.1	85.2
							362.0	324.4	290.7	260.3	233.1	208.9	187.2
								86.2	77.2	69.2	62.0	55.5	49.7
									69.1	61.9	55.5	49.7	44.5
										53.3	47.8	42.8	38.3
											44.0	39.4	35.3
												78.1	70.0
													116.4
	Sum=i	**118.3**	**214.4**	**412.1**	**580.2**	**703.9**	**992.0**	**975.5**	**942.9**	**897.9**	**848.6**	**838.2**	**867.4**
2nd year	March value of i $\times e^{-kt}$ =ii′	777.2	696.5	623.7	558.6	500.5	448.4	401.6	360.0	322.7	288.8	258.5	231.6
	i+ii′=ii	**895.5**	**910.9**	**1035.8**	**1138.8**	**1204.4**	**1440.4**	**1377.1**	**1302.9**	**1220.6**	**1137.4**	**1096.7**	**1099.0**
3rd year	March value of ii $\times e^{-kt}$ =iii′	984.7	882.5	790.2	707.8	634.1	568.2	508.8	456.1	408.8	366.0	327.5	293.4
	i+iii′ =iii	**1103.0**	**1096.9**	**1202.3**	**1288.0**	**1338.0**	**1560.2**	**1484.3**	**1399.0**	**1306.7**	**1214.6**	**1165.7**	**1160.8**
4th year	March value of iii $\times e^{-kt}$ =iv′	1040.1	932.1	834.6	747.6	669.8	600.1	537.4	481.7	431.8	386.5	345.9	309.9
	i+iv′ =iv	**1158.4**	**1146.5**	**1246.7**	**1327.8**	**1373.7**	**1592.1**	**1512.9**	**1424.6**	**1329.7**	**1235.1**	**1184.1**	**1177.3**
Steady state	Nat. decay of flow due to previous years.	1060.3	950.3	850.9	762.1	682.8	611.8	547.9	491.1	441.1	394.1	352.7	316.0
	„+i	**1178.6**	**1164.7**	**1263.0**	**1342.3**	**1386.7**	**1603.8**	**1523.4**	**1434.0**	**1339.0**	**1242.7**	**1190.9**	**1183.4**

state, i.e. 1321.0, we have the mean spring discharge of rain water origin. Subtracting it from 11.49 litre/min., the annual mean of the observed discharge, we get the juvenile discharge, that is:

Mean discharge of rain origin $\overline{F}=1321.0\times 0.00390=5.16$ litre/min.

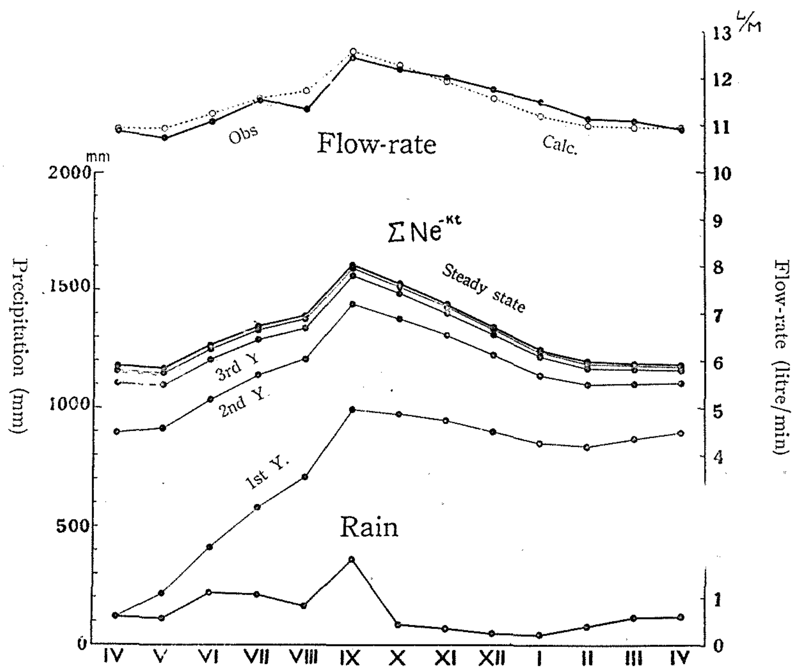
Discharge of magmatic origin $J=11.49-5.16=$ **6.33** litre/min.

Multiplying each monthly value of $\sum Ne^{-kt}$ in the steady state by a, we have F for the monthly discharge of rain water origin. The juvenile discharge $J=6.33$ litre/min. being added to this, we obtain the annual variation in the total spring discharge. The results obtained are given

Table 17. Calculated value of the 10 years mean of annual variation in flow-rate of Beppu springs.

Month	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III
Flow of rain-origin F	4.60	4.53	4.93	5.24	5.41	6.26	5.95	5.60	5.22	4.85	4.65	4.62
Total flow $F+J$	**10.93**	**10.86**	**11.26**	**11.57**	**11.74**	**12.59**	**12.28**	**11.93**	**11.55**	**11.18**	**10.98**	**10.95**

Fig. 8. ΣNe^{-kt} and the flow-rate coresponding to the mean annual change of precipitation in Beppu.



in Table 17. In Fig. 8, this calculated discharge is affixed to the observed discharge. The results obtained by calculation agree quite closely with those by observation.

One of the most important results in this chapter is the inference of the juvenile discharge. $J=6.33$ lit/min., the mean for 10 years, indeed corresponds to 55.1 % of the mean total discharge $Q=11.49$ lit/min. It is significant that the value nearly agrees with $J=6.1$ lit/min., in 1925, which was reached through a quite different way of inference. It denotes not only that the value is credible, but also that the juvenile water does not vary over a period of several years. In short, *about half of the hot spring water in the city of Beppu is the juvenile water of the magmatic origin*, and the assumption of magmatic activity in the area which was based on a comparison of the total precipitation on the catchment area with the total spring discharge in the city of Beppu is therefore supported. Although the value of a is somewhat larger than we found it in the preceding chap er, this must be due to the fact that in case of a heavy rain such as in September 1925, the run-off is big and the percolation small and so it has comparatively little effect as a feeding origin of hot springs. But as the water which has once percolated re-wells in the same state provided the underground path is identical, k may be regarded as unchanged.

3) *Study on the secular variation* :—Now, the secular variation in discharge mentioned in § 4 will be quantitatively explained from the rain which fell in the same years. Here, 'secular' means the period for 10 years from 1925 to 1935. During those years only 8 springs were consecutively observed. In spite of such insufficient data, the inferences drawn received unexpected confirmation from the observations.

The precipitation and the spring discharge are shown in Table 18 and Fig. 6. As the yearly differences of the mean atmospheric pressure and sea level are below 1/20 of the seasonal difference in the year, their effects influencing the discharge rate need not be taken into account, for they are within the observation error.

Table 18. Mean secular variation in the flow-rate of 8 springs compared with the precipitation

Year		1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935
Rain (mm)		2149	961	1522	1913	1732	1536	2289	1473	1502	1399	2374
Flow L/M	Obs.	15.39	12.39	12.68	13.36	12.82	11.74	—	10.96	9.01	9.29	11.75
	Corrected for natural decay	12.47	10.54	11.29	12.43	12.36	11.74	—	11.89	10.40	11.14	14.67

As has frequently been noted, the discharge from the same spring mouth presents a natural diminution by deposition or clogging through the conduit pipe, and therefore it must be revised before comparison with the rain. From the tendency shown in Fig. 6, take the total mean 11.94 litre/min. at 1930 as the centre and draw such a straight line as shows a difference of 0.463 lit/min. every 1 year before and after to represent the effect of natural wearing down. Correction corresponding to this has been made to the observed discharge and the values thus obtained are given in the lowest row of Table 18. Then explain the discharge rate thus revised with the secular variation in precipitation. Years to be dealt with are equal in the case of 2) and, therefore, the depletion index of the rain effect and the percentage of the juvenile water may be regarded the same as before, i. e. we may take

$$k=0.11, \qquad J=6.33\times\frac{11.94}{11.49}=6.58 \text{ lit/min.}$$

Then starting from the discharge rate in 1925, the rate of discharge in the following years can be calculated by the precipitation in a similar way as in the case of 1). The results obtained are given in Table 19.

Table 19. Calculation of the mean secular variation for 8 springs in Beppu.

Year	1925	1926	1927	1928	1629	1930	1931	1932	1933	1934	1935
		961	228	54	12	3	1	—	—	—	—
			1522	361	85	20	5	2	—	—	—
				1913	453	107	25	6	2		
					1732	410	97	23	5	2	—
Ne^{-kt}						1536	364	86	20	5	2
							2289	543	128	30	7
								1473	349	83	19
									1502	356	84
										1399	332
											2374
ΣNe^{-kt}		**961**	**1750**	**2328**	**2282**	**2076**	**2781**	**2133**	**2006**	**1875**	**2318**
$a\Sigma Ne^{-kt}$		2.31	4.27	5.73	5.69	5.20	6.88	5.37	5.04	4.70	6.95
$F_1=Q-J$	5.89	1.57	0.42	0.11	0.03	0.01	0	0	0	0	0
F_1+J	**12.47**	**8.15**	**7.00**	**6.69**	**6.61**	**6.59**	**6.58**	**6.58**	**6.58**	**6.58**	**6.58**
$F_1+J+a\Sigma Ne^{-kt}$	**12.47**	**10.46**	**11.27**	**12.42**	**12.30**	**11.89**	**13.46**	**11.95**	**11.62**	**11.28**	**13.53**

Here, F_1 means the natural decrease of $12.47-6.58=5.89$ litre/min., the part of rain origin in the revised discharge in 1925, and a is determined similarly as in the case of 1), as

$$a=\frac{\text{Total sum of }\{Q-(F_1+J)\}}{\text{Total sum of }\sum Ne^{-kt}}=\frac{45.10}{18855}=0.0024,$$

which was used in the calculation of $a\sum Ne^{-kt}$.

It is shown in Fig. 6 that the calculated discharge-rate given in the lowest row of Table 19 almost agrees with the observed rate revised in Table 18. To the same figure, the observed water level of the hot spring well at the Miyadi-dake Shrine in the city is appended as a reference since it suggests an increasing tendency of spring discharge in 1931 although this was not evident by lacking observations. Here, it must be noted that the value of α for secular variation is comparatively smaller than in the previous case of annual variation. Even for the same hot springs, the effect of heavy rain may be different from that of drizzle. For instance, a short, heavy rain accompanying a typhoon, such as fell in September 1925, will result a comparatively small percentage of percolation; while in a long, gentle rain, such as in the rainy season, a larger part of the precipitation may percolate and make the value of α large, as we have already mentioned. Moreover, if the springs under consideration are different, having different subway or nature of the ground, the effect of the precipitation will naturally be different. As the springs used for the study of the annual variation were numerous covering the whole city in both cases of the year 1925 and of the mean for 10 years, they may be regarded as the case of the same hot springs with the same subway, and consequently, the difference of α may be attributed to the character of the rainfall. But the springs used for the study of the secular variation were 8 in number, 7 of which were near the coast and only one was on the Bluff. Therefore, α may be quite different from the mean of the great number of springs throughout the city.

It is very significant that the α obtained here for the springs which are far from the Bluff and near the coast is smaller than the α obtained previously for the mean for the whole city, for it shows that the effects of rain is strong on the Bluff and weak at the coast. This fact agrees with the result of another study, 'the distribution of influences of rainfall in the Beppu hot springs'.[1] But we do not adhere its value $\alpha = 0.0024$. For, in the case of different springs whose subways are different, not only α but k may be different. Therefore, even for the above study on the special 8 springs, there may be some objection to using $k=0.11$, the mean for the whole city; but it is unavoidable, for we have now no way to derive a more accurate value. If k varies, α would also vary with it.

VI. Conclusion

The relation between the spring discharge and rain in the Beppu hot springs has been discussed. The chief points are as follows:

1. Tikyu-Buturi (Geophysics), 2 (1938), 152.

(1) The total discharge for a year of the Beppu hot springs in the old city, is so great as to reach 16% of the total precipitation on the watershed area, preserving such high temperatures that the mean is 53°. What wonderful heating power the Beppu zone holds which raises all at once such a great amount of water to such a high temperature year in year out. There can be few examples like it in the world!

(2) The hot spring water is fed by juvenile water and rain water. A large amount of the percolated rain becomes hot water, and besides, 55% of the total hot discharge is juvenile water. It is easily understood from this evidence what an active magmatic area the Beppu hot spring zone is situated on.

(3) The hot springs vary considerably with the seasons. Both spring discharge and temperature rise in the warm seasons and fall in the cold ones. Besides,

(a) The annual variation in discharge is caused by the annual variations in precipitation, atmospheric pressure, and sea level, and their influences bear such ratio as:

Rainfall : Atmospheric pressure : Sea level = 5 : 2 : 1

(b) The annual variation in spring temperature is caused partly by the change in discharge-rate and partly by the atmospheric temperature, bearing the ratio 2 : 3. The former is caused by the fact that the heat of hot spring water is absorbed on the way from the spring origin to the upper end of welling mouth and the water is cooled; the latter, by the fact that it is cooled by the earth or the air at the upper end of welling mouth.

(4) The hot spring fluctuates as years go by, that is, it presents a secular variation. As to special welling mouths in the Beppu hot springs, the conduit pipes are clogged by deposition of incrustation (Fig. 9), or the leakage is increased by corrosion of the pipes. On account of these hindrances at individual springs, the discharge rate shows a diminution year by year, so that the mouths must be dredged or redug every 10 years on the average. But that the total discharge of hot springs under the whole city of Beppu by no means shows a decline is proved by the investigations in 1924 and 1933. But in addition to the seasonal variation the spring discharge varies yearly with the change in yearly precipitation. However, as the yearly differences of mean atmospheric pressure and sea level are less than 1/10 compared with the seasonal differences, their effects drop within the observation error and may be left out of consideration. Similarly, the

difference of yearly mean atmospheric temperature being little, its influence hardly contributes to the secular variation of hot spring temperature.

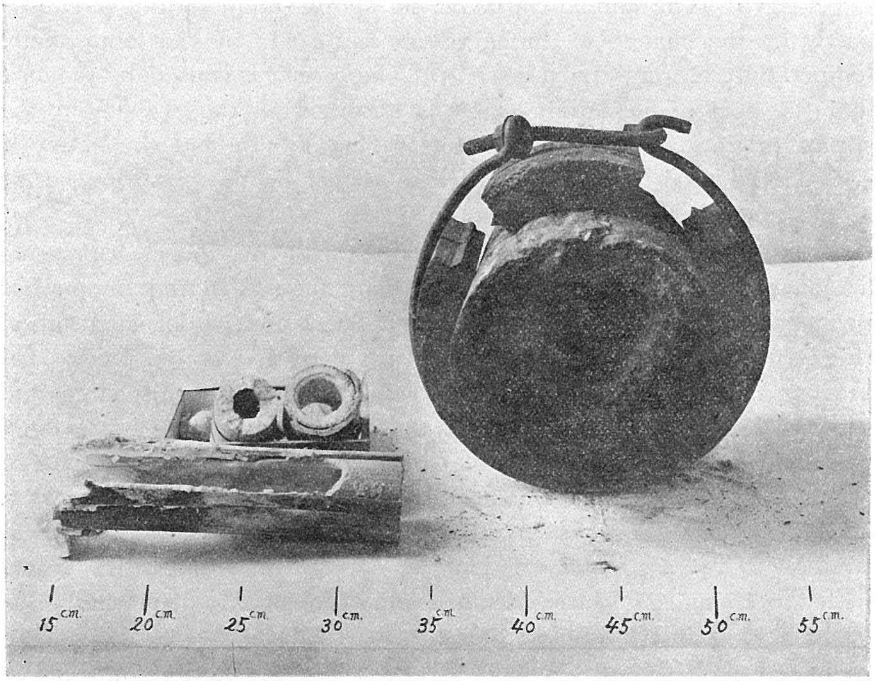
(5) The effect of precipitation on the spring discharge appears remarkably within the month, but it persists for about 3 years, that is, it has an after effect. Generally the after effect of rain exponentially decreases with time. Namely, it forms aNe^{-kt} where N stands for the precipitation (mm.) and t for the time after rain.

(6) We have shown a way of calculating from the observed discharge the coefficient of the after effect of rain a, its index of decrease k, and the juvenile water J. Measuring the precipitation and the spring discharge by the mm. and lit/min. respectively as units, we have obtained the following mean for the springs in Beppu;

$$k=0.11 \text{ (month unit)}, \qquad a=0.0039, \qquad J=6.3 \text{ litre/min.}$$

These three values having been decided, prediction of the welling discharge becomes possible if the rain can be predicted.

Fig. 9. Deposits on the wall of conduit pipe.



(a) Vertical pipe. (b) Horizontal pipe.