東京大学愛知演習林における森林水文に関する研究

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短　報

Studies on Forest Hydrology in the Tokyo University Forest in Aichi*

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I. Outline of the Tokyo University Forest in Aichi

The Tokyo University Forest in Aichi consists of seven blocks. Four of them are located in Seto City, two in Inuyama City, both cities located in Aichi Prefecture, and a block in Shizuoka Prefecture, with the total area being 1,310 ha.

The forests in Aichi Prefecture were established in 1922 for the purpose of the field works on water conservation, erosion control, and land surveying, and the forest in Shizuoka Prefecture, in 1928, for the sand dune fixation experiments.

From the viewpoint of forest zone, Seto and Inuyama belong to the northern region of the warm-temperature zone. However, the repeated destructive cutting before and after the Meiji era hampered the succession of forest vegetation and, as a result, *Pinus densiflora* forests with poor growth have been reproduced. And at present, broad-leaved trees, such as *Quercus grandulifera*, *Q. variabilis*, *Castanea crenata*, and *Ilex pedunculosa*, are growing under pine trees.

The main subjects for research exist in water conservation, erosion control, management or improvement of forests of low quality, and sand dune fixation.

II. Stream-runoff Gauging Project

1) Purpose

The purpose of the project consisted in the accurate recording of discharges from comparatively small watersheds in mountain area and the interpretation of complex hydrological phenomena obtained through it, presenting basic data for studies on forest influences, especially the effect on water regulation.

2) Watersheds experimental operations are shown in Table 1, 2 and 3.

3) Location of watersheds : Fig. 1

4) Description of watersheds (3)

(1) Ananomiya watershed

Area : 13.9 ha

Geology : Deep-weathered granite, being contiguous to tertiary formation.

Vegetation : Denuded land, partially covered by mixed trees. Afforestation for the purpose of erosion control was carried out on an area of about 4 ha from 1924 to 1928. The forest stands at present consists of 9.5 ha of pine and needle juniper (*Juniperus rigida*) on thinly-developed layer of forest soil ; 4.0 ha of weeds and mixed trees ; and 0.4 ha of denuded or degraded land with no vegetative cover.

(2) Higashiyama watershed

Area : 106.7 ha

Geology : Deep-weathered granite.

Vegetation : 59.3 ha of natural forest mainly of pine (40 to 50 years old) on well-formed forest soil layer ; 38.0 ha of pine and other trees on thin forest soil layer ; and 9.4 ha of denuded or degraded land with no vegetative cover.

(3) Shirasaka watershed

Area : 88.5 ha

Geology : Deep-weathered granite.

Vegetation : 68.8 ha of natural forest mainly of pine on well-formed forest soil layer ; 11.4 ha of afforested land with Hinoki (*Chamaecyparis obtusa*) on well-formed forest soil layer ; 7.4 ha of denuded or degraded land with no vegetative cover ; and 0.9 ha of asphalted roads.

(4) Kazunari watershed

Area : 109.6 ha

Geology : Tertiary formation of gravel overlying sandy clay horizontal.

Vegetation : 75.5 ha of denuded land interspersed with stunted pine and other trees ; 28.7 ha of denuded or degraded land with less vegetative cover ; 4.7 ha of paddy field ; and 0.7 ha of roads.

Topographical features : Table 4

5) Observation

(1) Rainfall observation

Day-raingauge : Observation is held at 9 : 00 a.m., the minimum scale of reading being 0.1 mm.

One-day self-registering raingauge : Recording paper is replaced at 9 : 00 a.m., the time

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Table 1. Watersheds

No.	Location	Watershed	Operation	
			From	To
1	Mizuno-cho, Seto City	Ananomiya	1923	now
2	Shinano-cho, Seto City	Higashiyama	1928	now
*3	Akazu-cho, Seto City	Shirasaka	1929	now
4	Mizuno-cho, Seto City	Kazunari	1930	1945

Table 2. Sub-watersheds in Shirasaka

Location	Sub-watershed	Operation	
		From	To
Shirasaka watershed	Kitadani	1949	now
ditto	Minamidani	1949	now

scale being 15 mm for an hour and the gauge scale 1/5.

(2) Water-level observation

Point gauge : Observation is held at 9 : 00 a.m., the minimum scales of reading being 1 mm for principal watersheds and 0.1 mm for sub-watersheds.

One-day self-registering water-level gauge : Recording paper is replaced at 9 : 00 a.m., the time scale being 15 mm for an hour and the gauge scales being 1/5 for principal watersheds, 1/4 for sub-watersheds, 1/2 for ground water, and 1/4 for well water level gauging.

Table 3. Observation of ground-water discharge and aquifer water-level fluctuations

Location	Sub-watershed	Operation	
		From	To
Shirasaka watershed	Kitadani	1957	now
ditto	Minamidani	1957	now

(3) Meteorological observations cover day evaporation, atmospheric temperature, soil temperature, wind velocity, cloudiness, insolation, and barometric pressure

6) Designs of stream-flow gauge stations and formulae for runoff calculation

Rectangular notch weirs are used for principal watersheds.

The discharge formulae are

$$h \leqq H : q = C_1 B_1 \sqrt{2\,g}\, h^{n_1}$$

where q=flow rate, h=water level

$$h \geqq H : q = C_1 B_1 \sqrt{2\,g}\, h^{n_1} + C_2 N B_2 \sqrt{2\,g}\, (h-H)^{n_2}$$

where H=the difference in height between the notch of the center and notches in wing positions ; N=number of wing notches

V-shaped and V-shaped notch weirs are used for

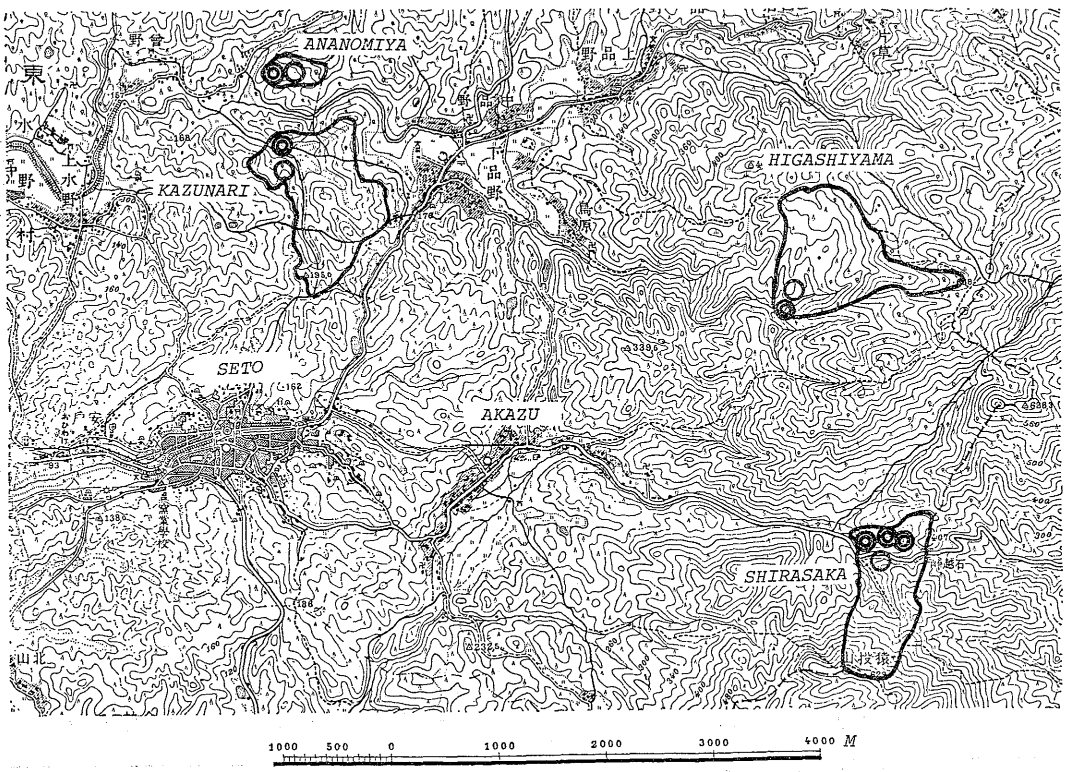

Fig. 1. Location of watersheds and gauging stations
◎ Stream-flow gauging station, ○ Rain gauging station

Table 4. Topographical features of watersheds

Station	Watershed area (hr)	Relief amount (m)	Mean gradient	Mean width (m)	Valley density (1/km)	Watershed compactness
Ananomiya	13.9	77.0	19.0	240	4.17	0.79
Higashiyama	106.7	270.5	25.0	220	4.47	0.67
Shirasaka	88.5	335.0	25.0	320	3.09	0.69
Kazunari	109.6	31.9	13.5	270	3.65	0.59
Shirasaka North V.	1.19	45.0	22.0	150	6.67	0.84
Shirasaka N. Ground water	0.44	20.0	—	—	—	0.61
Shirasaka South V.	1.42	55.0	29.5	78	12.82	0.91
Shirasaka S. Ground water	0.48	30.0	—	—	—	.8)

Table 5. Designs of stream-flow gauging stations

Station	Notch type	Center notch width B_1(m)	Side notch			c_1	n_1	c_2	n_2
			H(m)	B_2(m)	N				
Ananomiya	Rectangle	0.2	0.2	1.0	2×2	0.413	3/2	0.427	3/2
Higashiyama	Rectangle	0.2	0.4	1.0	3×2	0.437	3/2	0.416	3/2
Shirasaka	Rectangle	0.2	0.5	1.0	6×2	0.369	3/2	0.398	3/2
Kazunari	Rectangle	0.2	0.5	1.0	6×2	0.387	3/2	0.390	3/2

Table 6. Designs of stream-flow gauging stations for sub-watersheds

Station	Notch type	tan α	H (cm)	c_3 (cm)	n_3
Shirasaka North V.	V	0.5774	—	7.856	5/2
Shirasaka South V.	V	0.5774	—	7.856	5/2
Shirasaka N. Ground water	⩒	0.1000	17.9	2.603	2.30
Shirasaka S. Ground water	⩒	0.1000	18.8	1.855	2.40

Table 7. Designs of gauging stations

Station	Shape	Mean width (m)	Mean length (m)	Depth below zero (m)	Water level-surface area (m²)
Ananomiya	Spoon	17.0	22.0	1.5	$177.8\,h^{3.7}+70.0\,h+476.0$
Higashiyama	Rectangle	17.0	20.0	1.5	$61.8\,h^{0.84}+271.5$
Shirasaka	Rectangle	20.5	15.0	1.5	$11.6\,h+361.1$
Kazunari	Rectangle	20.0	22.5	1.5	450.0
Shirasaka North V.	Rectangle	6.0	9.1	1.5	$3.84\,h+51.0$
Shirasaka South V.	Rectangle	6.0	9.1	1.5	$4.23\,h+51.1$

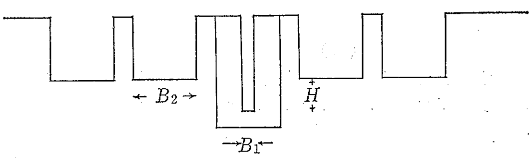

Fig. 2. Dimension of stream-flow gauging stations

sub-watersheds, the respective flow formula being

V-notch ; $q=C_v \tan\alpha\sqrt{2g}\,h^{n_3}=C_3h^{n_3}$

⩒-notch ; $q=C_v \tan\alpha\sqrt{2g}\,h^{n_3}$

$-C_v\tan\alpha\sqrt{2g}(h-H)^{n_3}$

$=C_3h^{n_3}-C_3(h-H)^{n_3}$

where α= one half the opening angle of the notch ; H=the height of V-notch section

7) Retarding basins of the respective stream-flow gauging stations (*4*)

Regulation factor β by retarding basins :

$$(1/2)(Q_t+Q_{t+\Delta t})=(V/\Delta t+q/2)_{t+\Delta t}-(V/\Delta t-q/2)_t \quad (1)$$

$$(1/2)\ (Q_t+Q_{t+\Delta t})=\beta(q_{t+\Delta t}-q_t)+q_t \quad (2)$$

$$\beta=\frac{A}{\Delta t}\frac{1}{\frac{dq}{dh}}+\frac{1}{2}$$

where Δt=10 min ; Q_t, $Q_{t+\Delta t}$= inflow at time t and $t+\Delta t$; q_t, $q_{t+\Delta t}$= outflow at time t and $t+\Delta t$; V_t, $V_{t+\Delta t}$=volume of storage water at time t, and $t+\Delta t$; β=regulation factor

8) Hydrological features of watersheds

(1) Monthly rainfall and monthly flow averaged over the last 10 years (*4*)

Values calculated for Shirasaka watershed on the basis of the data of last 30-years observation ;

average annual rainfall : $\bar{P}$=1,854.5 mm

standard deviation : σ=281.0 mm

limits at confidence coefficient 99% : $P=\bar{P}\pm2.5\,\sigma$

P_{max}=2,557 mm, P_{min}=1,152 mm

(2) Equations of annual flow vs. annual rainfall (*1*, *5*)

Table 8. Values of regulation factor

Water level (m)	Ana. β	Higashi. β	Shira. β	Kazu. β	Shira. N. β	Shira. S. β	Shira. m³/min $V/\Delta t+q/2$	$V/\Delta t+q/2$
0.010	15.64	9.17	—	14.923	43.66	43.54	—	—
0.020	11.11	6.586	8.78	10.774	15.77	15.73	0.753	0.693
0.040	8.01	4.826	6.36	7.710	5.908	5.892	1.531	1.361
0.060	6.66	4.056	5.28	6.406	3.448	3.438	2.329	2.009
0.100	5.29	3.284	4.20	5.074	1.875	1.870	3.953	3.281
0.200	3.94	2.519	3.12	3.733	0.970	0.988	8.173	6.319
0.300	1.089	2.184	2.65	3.141	0.769	0.767	12.581	9.193
0.400	0.813	1.990	2.37	2.587	0.676	0.675	17.147	11.931
0.500	0.726	0.869	2.18	2.549	0.627	0.626	21.846	14.558
0.600	0.686	0.686	0.559	0.574	0.597	0.597	47.814	−4.058
0.700	0.665	0.626	0.542	0.553	—	—	90.386	−39.258

Table 9. Average monthly rainfall and monthly runoff

Monthly rainfall (mm)

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Ana.	57.4	76.8	107.1	106.1	136.2	214.1	248.4	146.7	216.8	119.1	65.0	62.4	1,610.0
Higashi.	61.2	82.1	122.3	189.1	157.4	230.8	275.0	167.0	220.3	138.0	70.7	63.6	1,774.2
Shira.	60.1	81.8	129.9	192.4	163.7	233.0	289.6	171.9	231.3	136.5	72.1	64.1	1,819.4
Kazu.	35.0	70.8	107.8	123.5	134.0	222.5	204.6	148.5	174.1	208.4	80.0	42.5	1,551.7

Monthly runoff (mm)

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total	Loss
Ana.	38.4	43.6	62.0	90.1	82.2	106.4	181.9	79.3	115.7	75.1	48.9	41.9	965.5	644.5
Higashi.	37.4	40.7	65.8	105.7	98.2	112.6	199.0	87.7	113.9	76.5	48.7	42.3	1,028.4	749.0
Shira.	33.4	34.5	61.2	97.6	92.6	109.7	208.1	91.7	120.5	73.9	46.0	39.6	1,008.8	810.6
Kazu.	28.1	39.1	62.8	63.5	68.1	114.5	139.0	67.1	90.2	125.7	57.5	38.0	893.6	658.1

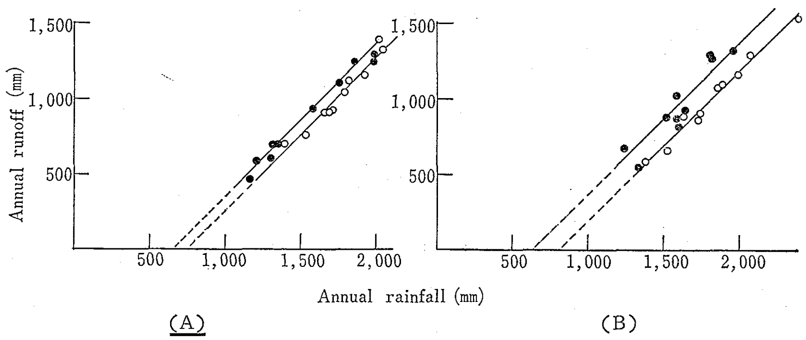

Fig. 3. Annual rainfall vs. annual stream-flow relation
(A) ○ Higashiyama, ● Kazunari (B) ○ Shirasaka, ● Ananomiya

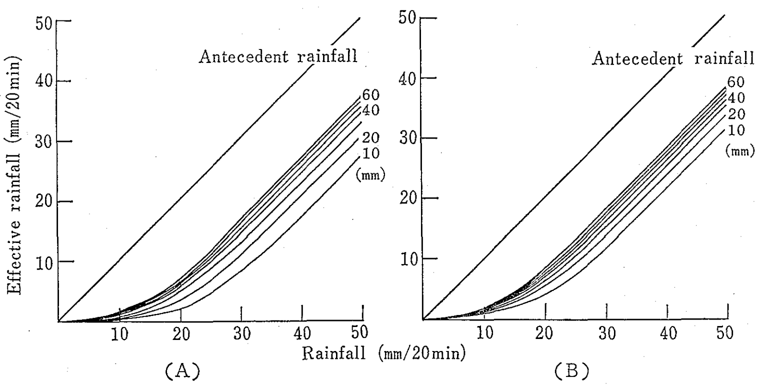

Fig. 4. Rainfall vs. effective rainfall relation
(A) Shirasaka, (B) Kazunari

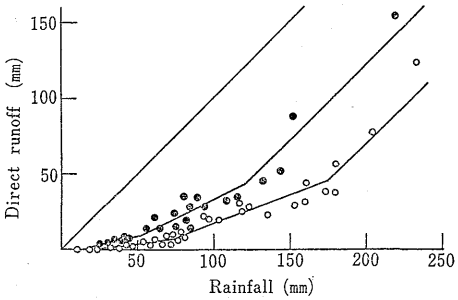

Fig. 5. Rainfall vs. direct runoff relation
○ Shirasaka, ● Kazunari

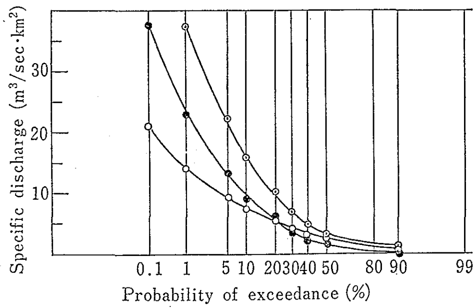

Fig. 8. Duration curve of annual maximum specific flow
⊙ Ananomiya, ○ Shirasaka, ● Kazunari

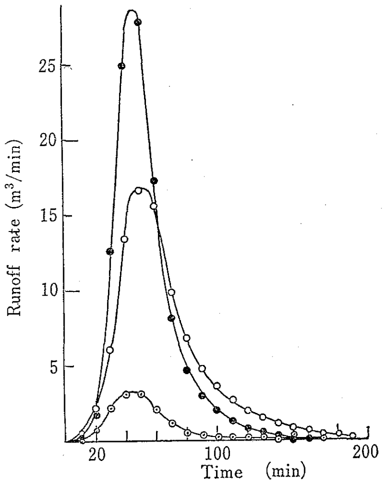

Fig. 6. Unit hydrograph
⊙ Ananomiya, ○ Shirasaka
● Kazunari

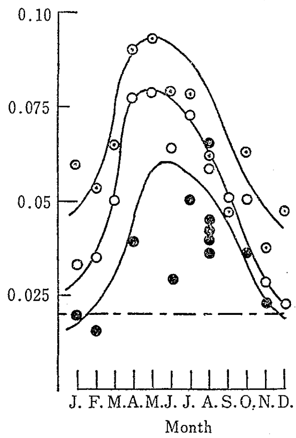

Fig. 9. Monthly values in α (1/day)
⊙ Ananomiya, ○ Higashiyama, ● Shirasaka

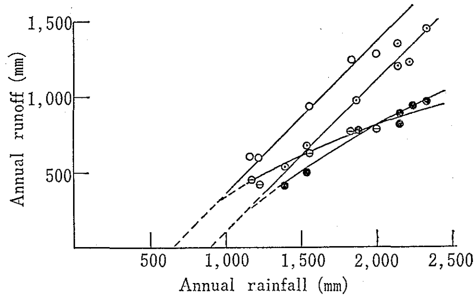

Fig. 10. Annual rainfall, annual runoff, annual loss and ground-water flow
⊙ Shirasaka runoff, ● Shirasaka ground water
○ Kazunari runoff, ⊖ Kazunari ground water

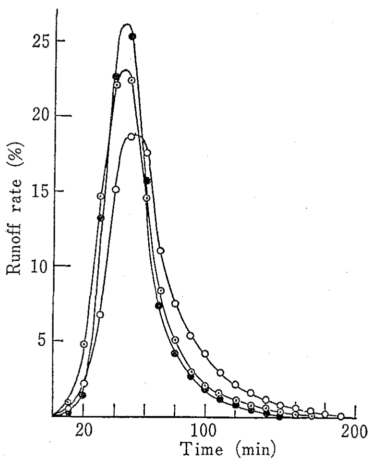

Fig. 7. Distribution graph
⊙ Ananomiya, ○ Shirasaka
● Kazunari

(a) $Q=P-L$

(b) $P^3-3LQP-Q^3=0$

(c) $q=P\alpha_1+\frac{P}{K}(\alpha_2-\alpha_1)e^{(K-1)}e^{-KP_1/P}$
$+\frac{P}{K}(1-\alpha_2)e^{(K-1)}e^{-KP_2/P}$

where P=annual rainfall ; Q=annual flow ; L=

Table 10. Annual maximum values in rainfall and runoff

	Year	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Ana.	Max. daily rainfall (mm)	83.5	129.0	86.5	130.7	81.8	83.5	174.5	217.4	114.0	86.5
	Max. runoff rate (m/sec)	0.096	0.806	0.355	1.096	0.308	0.106	0.312	0.399	0.247	0.197
	Specific discharge (m/sec·km)	0.690	5.799	2.551	7.885	2.217	0.759	2.244	2.871	1.773	1.414
Higashi.	Max. daily rainfall (mm)	96.7	111.3	92.0	144.0	92.7	120.0	150.3	240.0	156.5	93.7
	Max. runoff rate (m/sec)	0.568	3.263	1.018	3.999	1.581	0.755	1.589	1.522	3.274	1.115
	Specific discharge (m/sec·km)	0.533	3.058	0.954	3.748	1.482	0.708	1.498	1.426	3.068	1.045
Shira.	Max. daily rainfall (mm)	92.1	107.5	130.1	141.1	84.2	141.4	135.5	256.0	192.4	100.5
	Max. runoff rate (m/sec)	0.475	2.621	1.570	3.938	1.543	2.496	1.530	2.449	5.315	0.801
	Specific discharge (m/sec·km)	0.537	2.962	1.774	4.450	1.744	2.820	1.728	2.767	6.005	0.905
	Year	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945
Kazu.	Max. daily rainfall (mm)	188.9	52.8	94.9	62.7	153.5	204.8	105.1	71.2	51.7	120.2
	Max. runoff rate (m/sec)	11.856	1.114	0.546	3.709	3.357	24.298	6.053	1.102	0.461	11.462
	Specific discharge (m/sec·km)	10.818	1.016	0.498	3.384	3.063	22.170	5.532	1.006	0.420	10.458

Table 11. Monthly values in α (1/day)

	Ana.	Shira.	Higashi.
Jan.	0.047	0.017	0.028
Feb.	0.056	0.021	0.036
Mar.	0.071	0.027	0.057
Apr.	0.090	0.039	0.078
May	0.092	0.058	0.079
June	0.088	0.058	0.075
July	0.082	0.054	0.069
Aug.	0.075	0.049	0.062
Sept.	0.066	0.042	0.052
Oct.	0.055	0.034	0.039
Nov.	0.047	0.042	0.029
Dec.	0.045	0.019	0.023

annual loss ; p=annually averaged daily rainfall ; q=annually averaged daily flow ; p_1, p_2= critical daily rainfalls on areas with different initial losses ; α_1, α_2=percentages of areas of different initial losses to the total area ; K=constant related to the rainfall frequency, K=0.375

(3) Rainfall vs. effective rainfall relation (*4*)
The relations between 20-minute rainfall and effective rainfall as observed for Shirasaka and Kazunari watersheds are shown in Fig. 4.

(4) Unit hydrographs and distribution graphs (*2*)
Figure 6 and Fig. 7 show the unit hydrographs and distribution graphs of Ananomiya, Shirasaka, and Kazunari watersheds.

(5) The annual maximum values in rainfall and runoff rate during the last 10 years: Table 10
Duration curves of annual maximum specific flows for the respective watersheds are shown in Fig. 8.

(6) Ground-water depletion curves (*6*) : Table 11, Fig. 9

$$q=q_0e^{-\alpha t}$$

(7) Annual rainfall, annual flow, annual loss, direct flow, and ground-water flow, calculated for Shirasaka and Kazunari watersheds (*7*) : Table 12

Table 12. Annual rainfall, annual runoff, annual loss, and ground-water flow

Annual runoff (mm)	Shirasaka				Kazunari			
	Direct runoff (mm)	Ground water (mm)	Runoff (mm)	Loss water (mm)	Direct runoff (mm)	Ground water (mm)	Runoff (mm)	Loss water (mm)
1,200	40	260	300	900	80	440	520	680
1,400	70	430	500	900	160	560	720	680
1,600	130	570	700	900	250	670	920	680
1,800	200	700	900	900	380	740	1,120	680
2,000	290	810	1,100	900	520	800	1,320	680
2,200	390	910	1,300	900	680	840	1,520	680
2,400	500	1,000	1,500	900	850	870	1,720	680

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(*5*) ———: Role of forest resources in input and output of water in a valley. Water Sci. **6**(4): 19~28, 1962**

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* In Japanese with English summary
** In Japanese

(Received November 17, 1978)

抄　録

○サクラ，アリ，テンマクケムシ—葉が蜜を出してアリを惹きつけ，アリはケムシを捕食する

TILMAN, D. : Cherries, ants and tent caterpillars : timing of nectar production in relation to susceptibility of caterpillars to ant predation. Ecology **59** : 686～692, 1978

葉に蜜腺をもつ樹木では蜜を分泌することによってアリを惹きつけ，このアリが食葉性昆虫を捕食するので食害を少なくしているものと信じられている．この論文は，サクラ（*Prunus serotina*）の葉の蜜の分泌とアリ（*Formica obscuripes*）およびテンマクケムシ（*Malacosoma americanum*）との相互関係をしらべたものである。

開芽の時期には，サクラの葉のほとんどの鋸歯に蜜を分泌する蜜腺があり，その数は1枚の葉当り 60～90 に達する。1週間以内にその数は減少し葉身基部の2～5個を残すのみとなる。3週間経つと蜜腺はほとんどなくなる。葉は順次開いていくので，ひとつの芽当り（1シュート当り：抄録者）の蜜腺数はこれほど急激に減少するわけではないが，開芽時の4月12日に約 250 であったものが，4月20日には約 60，5月1日には8，5月15日にはわずか0.4となる。

蜜を分泌している新しい葉にやってきたアリは，そこに平均55秒滞在して吸蜜し，次に平均13秒をついやして別の葉に移る。1日当り活動アリ数は，開芽直後がもっとも高く以後は減少する。これは蜜の生産量の変化と対応している。アリの巣に近い木には遠い木よりもアリの数が多い。吸蜜中のアリが他の昆虫に出会うとそれを攻撃する。開芽した日には，アリがテンマクケムシの1齢幼虫を大顎でくわえて巣に運ぶのが観察された。しかし，このようなアリの捕食の機会は，ケムシが生長して大きくなるとともに少なくなる。開芽後3週間経つ4月末には，ケムシはアリの体長のほぼ2倍となり，アリはケムシと出会っても攻撃しない。

テンマクケムシの卵塊の分布は木の大きさと関係があり，大きい木により多く産卵される傾向があったが，アリの巣からの距離とは無関係であった。4，5齢のテンマクケムシは，アリの巣から 20m 以上のアリのほとんど訪れない距離にあるサクラの木に多い傾向があった。中齢以降の幼虫の摂食量が，ケムシ1世代の全摂食量の大部分を占めるものと考えられるから，アリの巣から遠い木はケムシによる食害量が大きいわけである。

以上の事実は，サクラの葉の蜜腺が捕食性のアリを惹きつけることによって食葉性害虫の被害を少なくする役割を果たしていることを示すものである。

（菊沢喜八郎）