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BIOENVIRONMENTAL AND RADIOLOGICAL-SAFETY FEASIBILITY STUDIES

ATLANTIC-PACIFIC INTEROCEANIC CANAL

HYDROGEN BUDGET AND COMPARTMENTS IN THE RAIN FOREST AT EL VERDE, PUERTO RICO, PERTINENT TO CONSIDERATION OF TRITIUM METABOLISM

by

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With Appendix

MATHEMATICAL FORMULATION OF THE HYDROGEN BUDGET MODEL

by

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FOREWORD

It has been estimated that more than 10^9 curies of tritium would be produced by the nuclear explosives required to excavate a sea-level canal across the isthmus of Central America. Most of the tritium released to the bioenvironment would probably be in the form of tritiated water and would be incorporated in the hydrological cycle. The studies included in this preliminary report were encouraged and accelerated to provide some advance insight into the probable routes and rates for the transfer of tritium within, and elimination from, a tropical forest ecosystem that is similar (during the wet season) in most essential respects to those of eastern Panama and northwestern Colombia.

This is a preliminary report on a phase of the Rain Forest Project of the Puerto Rico Nuclear Center on U. S. Atomic Energy Commission, Contract No. AT(40-1)-1833. The studies were aided by Purchase Order No. S-3946 from the Interoceanic Canal Commission survey as arranged by Battelle Memorial Institute, on U. S. Atomic Energy Commission prime Contract No. AT(26-1)-171, and by the direct participation of Battelle engineers Mr. Hobart Cress and Mr. Richard Egen. The report is based on instrument measurements by G. Drewry, J. Edmisten, P. Murphy, H. Watson, R. F. Smith, J. Kline, G. Cintron, and others. Dr. Howard T. Odum, author of the report, is presently associated with Wilson Laboratory of Zoology, University of North Carolina, Chapel Hill, North Carolina.

The data on water and hydrogen budgets are to be included in a chapter of the Rain Forest Book that is in preparation through the AEC Office of Technical Information.

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PRELIMINARY REPORT

HYDROGEN BUDGET AND COMPARTMENTS IN THE RAIN FOREST AT EL VERDE, PUERTO RICO, PERTINENT TO CONSIDERATION OF TRITIUM METABOLISM

ABSTRACT

From data on rainfall, throughfall, stemflow, evaporation, transpiration, percolation, photosynthesis, and respiration from the montane forest at El Verde, Puerto Rico, a hydrogen compartmental diagram with flow rates and compartmental storages is prepared (Figure 1). This diagram permits computation of transient phenomena for the flow of tritium in a tropical forest assuming a knowledge of the extent and the duration of the tracer input. A mathematical model for tritium transfer, based upon this diagram, is given in the Appendix. The story at El Verde is found to be somewhat comparable to that of Panama during its wet season as their rainfall and saturation deficits are similar.

INTRODUCTION

If tritiated water is released into a tropical forest, it constitutes a radioactive tracer in a large volume of water, from rain and condensation, that flows in and out of the forest and its soil components. The water flows involve the inputs of rain which then pass out of the main flow system by several exit routes: (1) as interception and evaporation from leaves, (2) as surface runoff, (3) through subterranean channels after percolation into the ground, (4) through transpiration of the vegetation, (5) as respiration of leaves and animals after some of the hydrogen of the transpiration stream is caught by the gross photosynthetic process, and (6) as long-term woody storages.

Any discussions and computations of the kinetics and residence time of radioactive-hydrogen injections require data on, (1) the size of the water and organic-matter storages in the various compartments of the forest system, and (2) the normal rates of hydrogen transport in the flows between compartments.

Although a several years' record of each flux is desirable to provide data of maximum accuracy for prediction, some magnitudes can be somewhat less accurately predicted from short-term records, especially for a forest with repeating regimes. With the studies underway in the Rain Forest at El Verde, some additional measurements were made during spring and summer of 1966 to provide estimates of the flows and compartments shown in Figure 1. As the records are for short periods, the accuracy is probably less than 25 percent in most of the means estimated. However, the budget synthesis made in Figure 1 does establish the relative orders of magnitude of the flow rates for a system in which the extreme flow rates differ by five orders of magnitude. Thus, some definite conclusions about the consequences of tagging and retention of tritium in this system are now possible. Some additional data now being gathered will permit improvement of the estimates although the magnitudes are not expected to change greatly. A mathematical model for tritium transfer based on Figure 1 is given in the Appendix.

The Flows and Compartments of Hydrogen in the Rain Forest

Figure 1 depicts the main compartments of hydrogen storage in water and in the organic compounds of leaves, limbs, wood, and litter. The inflow of water from rain and condensation is partly intercepted by the canopy and partly passes through the soil and drains away in the streams. The winds carry away the evaporation from the rain trapped on leaf surfaces, the evaporation from the ground, and the tree's transpiration stream, which pulls water up through roots and out the stomata of the leaves. A small fraction of the transpiration stream is bound into photosynthesis, of which a small part enters into the long-time storage of the biological structure, the longest storage being in the woody trunks.

To estimate the quantities of matter in the compartments and the average rates of flow, many kinds of measurements and calculations are involved. The numerical values in Figure 1 are the result of these computations. Figure 1 thus constitutes both the conclusion and summary of this report.

The flow rates were derived as follows:

Rainfall for June, 1966, was 12.53 inches - similar to the annual average of 11.5 inches.

Condensation input was estimated from measurements in a rain-shielded evaporation pan. During one-third of the nights, the water level increased by about 0.1 mm. If the pan represents condensation on other surfaces, then the leaf-area index, equal to 7 for this forest (Odum et al, 1963), may be used to estimate total condensation on 14 leaf surfaces and one ground surface. A similar evaporation rate was observed on the forest floor on many nights, but since the 15 surfaces were not wet, except when associated with rain, the net effect of condensation-evaporation from surfaces (not transpiration) is inward.

From Sollins and Drewrey's study (Rain Forest Book), 42 percent of the rain was taken as throughfall and 58 percent as interception followed by evaporation.

Runoff for June was derived from the weir records that were converted to discharge rates with a calibration curve.

Transpiration rates were taken from the evapotranspiration measurements in a giant cylinder over a 24-hour period. The measurements were made during a period following somewhat dry weather while the leaf surfaces were not damp, although the soil remained damp (February 24, 1966, 1.3 mm transpiration). The rate of photosynthetic fixation was taken (Odum, 1962) to be 8 g carbon/m^2/12 hours net during the day, and the rate of night respiration was taken to be the same value. Assuming that day respiration is equal to night respiration, the total gross photosynthesis was 16 g carbon/m^2/day, and the total 24-hour respiration was the same value. A similar figure was obtained with the giant cylinder on June 21-23, 1966. An animal metabolism rate of 0.05 g carbon per g dry weight of animal tissue per hour was assumed (Odum, 1962).

Rate of volume deposition of wood was taken as 0.02 percent of the existing volume (Murphy, Rain Forest Book).

Rate of litter deposition of 1.2 g dry-matter per day was taken from the team effort on litter fall designed by Dr. Wiegert (Rain Forest Book).

Rate of trunk run-down was found by Sollins and Drewry to be about 1 percent of total rainfall.

The rate of flow of water disappearing below the top 3 inches of clay was taken as the difference between the total runoff and the surface runoff on the assumption that both flows were at steady-state conditions. High rates of soil absorption were documented by Dr. Edmisten (Rain Forest Book). These rates were about 4 mm/min (mean of 36 measurements at the giant-cylinder site) when the water level was between 0.0 and 7.0 cm above the clay layer.

The storage quantities were obtained as follows:

Dry weights per unit area of the ground, obtained from studies in similar forests at Sabana, are given as: leaves, 812 g/m^2; tree stems and limbs, 5,237 g/m^2; animals, 4 g/m^2; litter and fine surface roots down to clay, 3,537 g/m^2 (Odum, Abbot, Golley, Selander, and Wilson, Rain Forest Book).

Water in the upper soil compartment was estimated from a bulk-density value of 1.05 g/cc (Edmisten) and a value of 47 percent of wet surface soil as water (Smith, Rain Forest Book). The following water contents, expressed as grams of water per gram of dry weight, were assumed: tree leaves, 2.9; tree stems and limbs, 0.7; litter surface roots, 4.8 from Rossy's (Rain Forest Book) measurements; and animals, 5.0. Conversions used were: 7 percent of organic dry matter as hydrogen; 50 percent of dry organic matter as carbon; and 1 mm of water depth as 1000 g/m^2.

EXPERIMENTAL METHODS

Different procedures were used to estimate each of the component processes of water movement at El Verde during the spring and summer of 1966. These procedures are described in the following sections. Many measurements were made in a giant cylinder which consisted of a cylinderical, plastic wall surrounding the experimental forest plot. This cylinder, along with some associated equipment and construction, is diagrammed in Figure 2.

Precipitation and Fraction Reaching Ground

Electrically recording, tipping-bucket gages had been recording on a weather tower about 100 meters from the giant-cylinder site. The percentage of penetration of water through the forest was obtained from two gages there, one located at 92 feet, well above the forest, and the other located under the canopy and receiving rainthrough. These data were studied and are reported by Sollins and Drewry. In the spring of 1966 a gage was placed above the giant cylinder on top of the 72-foot walk-up tower. The input of rain on this gage is recorded in the climate chapter of the Rain Forest Book.

Trunk Run-Down

At two sites, Sollin and Drewry measured the water that was running down trunks. Trunk run-down was measured with a trunk-circling rubber hose that diverted water through a tube and into the tipping-bucket rain gage. This water was prorated to the area of the tree crown to determine the percentage of the input passing down in this way.

Water Penetrating Down Through the Ground

As his assignment on the Rain Forest Project, Dr. Joe Edmisten, of the University of Georgia, devised a means for estimating the water drain into the ground by using bottomless aluminum cans. Seven centimeters of water were introduced into the can as a hydrographic head and the time for drainage was recorded. These numbers may be used as estimates for drain-through rates for that percentage of the time during which there is substantial water covering the ground. The results of this study, in a separate chapter of the Rain Forest Book, confirm the very porous nature of the forest floor. The porosity is due to friable structure of the loose clays.

Pan Evaporation

A water pan and mechanical chart recorder (Epic Company) were placed about a meter above the ground in summer, 1966, to gain an independent estimate of the water evaporation rate from a comparable surface. Later they were placed on top of the 72-foot walk-up tower. The evaporation from the pan was recorded on an ink chart as shown in Figure 3 and the data are summarized in Tables 1 and 2. Pan evaporation above the forest was somewhat of a check on total evapotranspiration, and when the pan was on the ground, it helped to estimate surface condensation as well as evaporation in the forest microclimate. The pan was shielded. The error in extending estimates of condensation from a water surface to the top and bottom of leaf surfaces is not known. The mean evaporation from the top of the tower was 0.46 mm at night and 1.38 mm during the day as shown in Table 1.

TABLE 1. EVAPORATION FROM TOP OF TOWER AT EL VERDE, PUERTO RICO

Month	Days Recorded	Mean Evaporation, mm		
		Daily	Nightly	24 Hour
August, 1966	18	1.36	0.41	1.74
September, 1966	17	1.83	0.52	2.36
October, 1966	14	1.12	0.50	1.62
November, 1966	22	1.31	0.43	1.77
December, 1966	31	1.14	0.39	1.49
January, 1967	7	1.50	0.60	2.10
Mean	--	1.38	0.46	1.84

TABLE 2. EVAPORATION NEAR THE FOREST FLOOR WITH AN EPIC EVAPORIMETER, 1965

Date	Change per Day[(a)]
June 1	-0.10
June 2	+0.50
June 3	-0.10
June 17-20	0.0
June 20-27	0.0
June 27	0.0
June 28	+0.45
June 29	-0.05
June 30	+0.20
July 1	+0.90
July 2	+0.60
July 3	+0.10
July 5-11	0.43/6 days or +0.07
July 11-14	0.0

(a) + is evaporation; - is condensation.

Throughfall

The most critical number in the calculation is the percent throughfall in which rain coats the broad leaves and then drips through to the ground. Two sets of measurements from rains of varying intensity were made by Sollins and Drewry from several months of records. The throughfall of 41.6 percent determined by this work from tipping-bucket records (Figure 4) approximates the 43 percent reported by Clegg (1963) in another study at El Verde. In this previous study, cans were placed in clearings and compared with other cans placed under the canopy. The average value in the present study was obtained by summing the products of the individual percentages and rainfalls and then dividing by the total rainfall. Of the 12 rains studied, the throughfall varied from 25 to 80 percent. Sollins and Drewry found a higher throughfall of 73 percent from measurements taken under a different canopy position, where the canopy was apparently less.

Hydrographic Weir

The planning of a small weir was done by Mr. Larry Hill of the Institute of Tropical Forestry of the U. S. Department of Agriculture. Using plans provided by the USDA (Holtan, et al, 1962), a standard 1-foot H flume was constructed and mounted on a concrete platform within the forest and below the giant cylinder (Figure 5). Mr. Richard Tegen of Battelle Memorial Institute arranged a Stevens water-level recorder for indicating height of water in the weir during substantial runoff, and for slight runoff, a trough was arranged to drain water into a covered barrel. This barrel was checked daily by Mr. Alejo Pinto who measured the water that accumulated during the day. As shown in Figure 2, a 6-inch trench was cut into the ground to a depth of about 3 inches around the giant cylinder. The trench avoided main rocks and passed under and around main roots. A 6-inch galvanized "tin" strip was placed as an outside trench wall. The strip was continued as a wall around the top of the cylinder and thus cut out any runoff from farther uphill. Cement was used to form a trench floor and to seal the tin wall firmly to the ground. The trench from the two sides of the cylinder was brought together so as to discharge water into a tin flume leading down to the weir. As constructed, the system could catch any water running off the surface or running through the litter and upper root layers. Water that penetrated more than 3 inches into the ground and passed into the red clay, was considered as water draining into the ground. The float records during heavy discharges were converted into water discharge data using calibration tables from the Agriculture Handbook. These calibration values are graphed in Figure 6. The weir records for days with runoff in June, 1966, are included in Figure 7.

Evapotranspiration

The evapotranspiration in the giant cylinder was measured by the change in grams per cubic meter of water vapor in the air from the time it entered the giant cylinder at the top until it passed out through the large fan at the ground level 5 minutes later. Details of the procedures for measuring and calculating the humidity in the flow are given in a Rain Forest Book chapter. The cylinder method estimates the total respiration but underestimates the photosynthesis of the crown when air is lost upward in eddies. Thus, the respiration rate may be used as an estimate of photosynthesis since the two processes must be equal over the long range. Selection of records to include some data after periods of no rain gives estimates of transpiration of the vegetation as there are no wet surfaces due to recent rain. Somewhat larger values found just after a rain indicate some direct evaporation and the possible stimulation of transpiration. Two records are given in Figures 8 and 9.

Photosynthetic Fixation and Respiration

The water passing through the transpiration stream to the leaves is mainly transpired, but a small fraction is fixed into organic matter by net photosynthesis in the various compartments of the forest. Some of these compartments are large with slight inputs so that the turnover time is large, whereas other compartments are very small or have massive flows so that turnover time is measured in minutes. Estimation of maximum possible retention of radionuclides entering with water thus depends in part on the size of the compartments and in part on the flow rates. Some magnitudes for respiration and for gross photosynthesis, with its temporary deposition as net organic gain, are indicated in the flow circuit of Figure 1.

As covered in two chapters of the Rain Forest Book, much of the gross photosynthesis of a day was used the following night in respiration. The respiration, however, includes part of earlier storages. For example, in the litter, microorganisms decomposed leaves that were grown months earlier. Some of the decomposing wood had been synthesized hundreds of years earlier. Night respiration in the giant cylinder was 0.51 g carbon/m^2/hr (mean of 5 days in 1966). The total photosynthesis is assumed to equal this.

Stage on Smaller Streams

There is a vast difference in stream flow between the flood stage following heavy rain and the trickle observed after several days of no rain. Whereas stage records were not obtained on the main Sonadora River during the period, a water-level float record was arranged by Mr. George Drewry on a permanent collecting brook located downhill from the giant-cylinder site at an elevation of 390 feet. This relative record provided some idea of the regime in the intermediate size streams that are kept permanently flowing by ground-water contributions during dry periods. A view of the float transducer is shown in Figure 10 and the record is summarized in Figure 11.

The stage could not be calibrated with volume discharge because of the large flows deep within the boulders and gravels of the stream bed, but the time constant was obtainable for this compartment.

Tree Growth

The rate of incorporation of wood was obtained from tree-trunk-increment studies by Mr. Peter Murphy as reported in detail in the Rain Forest Book. The increments were measured with aluminum vernier tapes on 250 trees of five principal species and computed as basal area increase. The ratio of new basal area to existing basal area provides the percent of the wood mass that is renewed and/or added each year. From the means, one may estimate the rate of fixation of organic hydrogen in tree trunks since the basal area of the forest is known in several plots.

Litter Fall

The team effort in collecting litter fall is summarized by R. Weigert. Since neither the optical density nor the litter cover changes much, the litter and leaves must be in a steady state. Thus, the leaf fall provides rates of flux of organic hydrogen into the litter and into leaf storage.

Soil Moisture and Density

Data on soil moisture reported in the Rain Forest Book were determined by oven drying soil for 48 hours at about 105 C. These data were used to estimate water storage in surface soil zones. Soil bulk density was found by Dr. J. Edmisten.

RESULTS

Various measurements were made to estimate flow and storage of water and, in almost every case, the resulting data establish orders of magnitude and indicate the kind of full-year study that could establish more accurate means.

The very large flow of rain water is divided with much of it being lost immediately as evaporation from the canopy surfaces or passed instantly out of sight into the porous surface structure. In the heaviest rains there is enough surface water to cause runoff or to establish a head for driving the water deeper into the ground. The runoff volume is occasionally large.

The flows of water by transpiration and by ground evaporation are relatively small but steady. The ground remains moist and receives condensation on many nights.

Even smaller are the flows of water into the photosynthetic process, most of which emerge as metabolic water, with a very tiny amount bound in long-time storages of wood.

DISCUSSION

Behavior of Tritiated Water in the Forest System

An examination of the rates of flow and the storages maintained in the forest system gives basis for discussion of the behavior of a charge of tritiated water introduced into the forest system. The main water compartments are the surface soil zone and the tree leaves and limbs. Except for extended dry spells of a week or two, the water flows are, on the average, turned over daily. Thus, there is little opportunity for tritium retention in these compartments for more than a few days beyond the time of active input of radioactive water.

The organic matter compartments incorporate hydrogen from water in photosynthesis and some water is deposited into long-time storages of wood. The turnover of the leaf and litter compartments is longer, so that 2 years might be required to discharge accumulations. However, the input of tracer would have to be maintained for many days before the compartment could accumulate an appreciable fraction of the tracer concentration. The wood compartment with its very long storage time constitutes a sink, but the concentration relative to the whole log would be very small since the annual wood-deposition rate is about a tenth of an inch.

Thus, the hazard of storing and keeping much tritium in the forest is great only if the input to the biological system is a high level of tracer maintained for a long, steady period. For forests on hills and mountains, the water flux is all downward, and there seems to be no means for holding such high tracer levels in the face of the rain flows.

The fact that high specific activities are possible in wood rings might be considered as a beneficial tool for widespread forestry study at El Verde and elsewhere.

Since in seasonal forests as in the Darien, Panama, some flows stop for 4 months, storage might be held for the dry season before fluxes in and out are resumed.

Comparison with USGS Study for Puerto Rico

Bogart, Arnow, and Crooks (1964) place the El Verde site in perspective with regard to conditions that change with altitude. These authors found 39 percent of the rain running off for the whole of Puerto Rico, but for the drainages from the high mountain zones the percentages were much higher, being 75 percent where the rain was 108 inches from Rio Toro Negro and 85 percent where the rain was 211 inches from Rio Hicaco. These higher runoffs reflect the lack of evapotranspiration within the high, cloud-shrouded forests as well as the greater percentages that drip through the leaves when the leaves stay wet. The El Verde site with 29 percent runoff during a wet month, represents a montane situation. The altitudinal range in Puerto Rico provides a scale for other areas of the moist tropics whose saturation deficits and rainfalls cover the same range.

Comparison with Panama

Like Puerto Rico, the Isthmus of Panama also receives trade-wind air and develops rainfalls of 80 to 200 inches mainly over an altitudinal range from sea level to 5000 feet. In Figure 12 the saturation deficits for Panama during wet and dry seasons are compared with those of Puerto Rico. The regime in the lower mountains of Puerto Rico and the regime in Panama, during the wet season, are comparable in their tendency for evaporation. Evaporation rates from pans in Panama are 76 to 200 mm per month. These rates are correlated with saturation deficits in Figure 13. Annual evaporation from a low-altitude area in Puerto Rico (San Juan) is given as 2115 mm or about 173 mm per month and this is within the Panama range. From Figure 1, daily evapotranspiration from the El Verde forest is 1.3 mm. Stanhill (1965) suggests that pan records are a good approximation to potential evapotranspiration.

In other words, the hydrogen and water budget estimates from the El Verde site are likely to resemble those of the moist forests of Panama for the wet season, especially in the range from sea level to 1500 feet. The runoffs within the cloud shrouded elevations are likely to be higher as indicated in the USGS data from Puerto Rico, as shown in Figure 14.

Comparison with a Temperate Forest

From temperate-forest data given by Ovington (1962) a diagram like that for the El Verde rain forest is prepared as Figure 15. Generally the temperate-forest numbers for storage and flux are smaller, but the turnover times may be similar. Net wood deposition rates are considerably greater.

A useful table reviewing water budgets from the literature on temperate watersheds was prepared by Ovington (1962).

CONCLUSION

The hydrogen budget in the water and organic compartments of the tropical rain forest are characterized by rapid turnover except in its woody storages. These woody storages are slowly entered and slowly discharged so that large quantities of tracer would become fixed only if the input of tracer to the system were maintained for a long time. A short exposure to high levels of tritiated water would result in a very thin but high-activity growth ring throughout the forest. Under ordinary uses to which wood is put, such a thin increment would be diluted by ordinary wood. An estimate of the actual quantities can be computed from Figure A-1 in the Appendix.

FURTHER STUDIES

Some calculations used in this report involve only a month's record, although this month is believed to be reasonably representative. Runoff, evaporation, and condensation measurements should be recorded for a year. The throughfall data from El Verde need further verification since the long-time records are from only two sites. Some independent check, using a gravimetric lysimeter, of the water draining into the soil might be desirable. To confirm the predicted behavior of tritium in the forest ecosystem, a tritium-tracer experiment is being conducted at El Verde.

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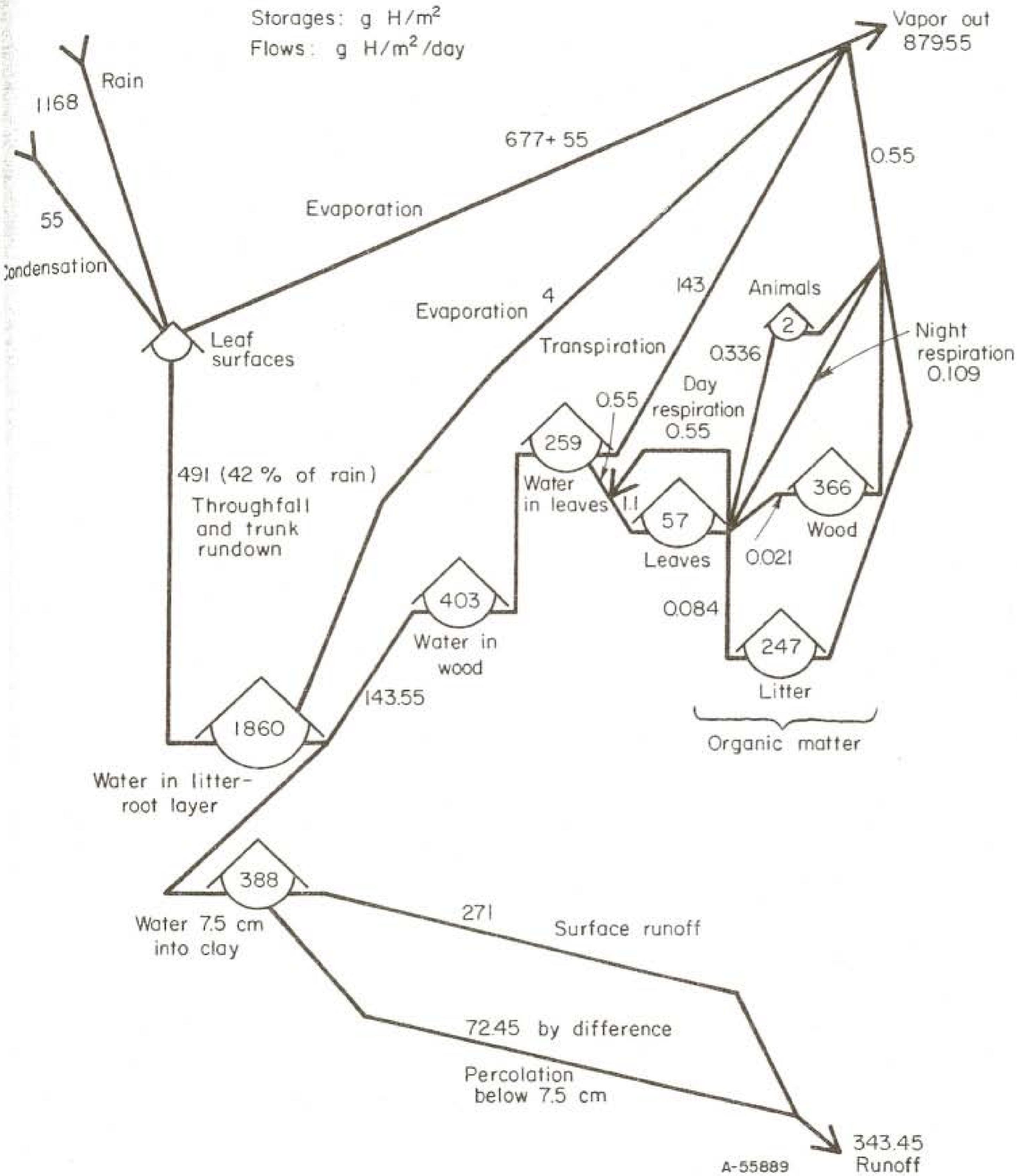

FIGURE 1. HYDROGEN BUDGET IN THE RAIN FOREST AT EL VERDE, PUERTO RICO

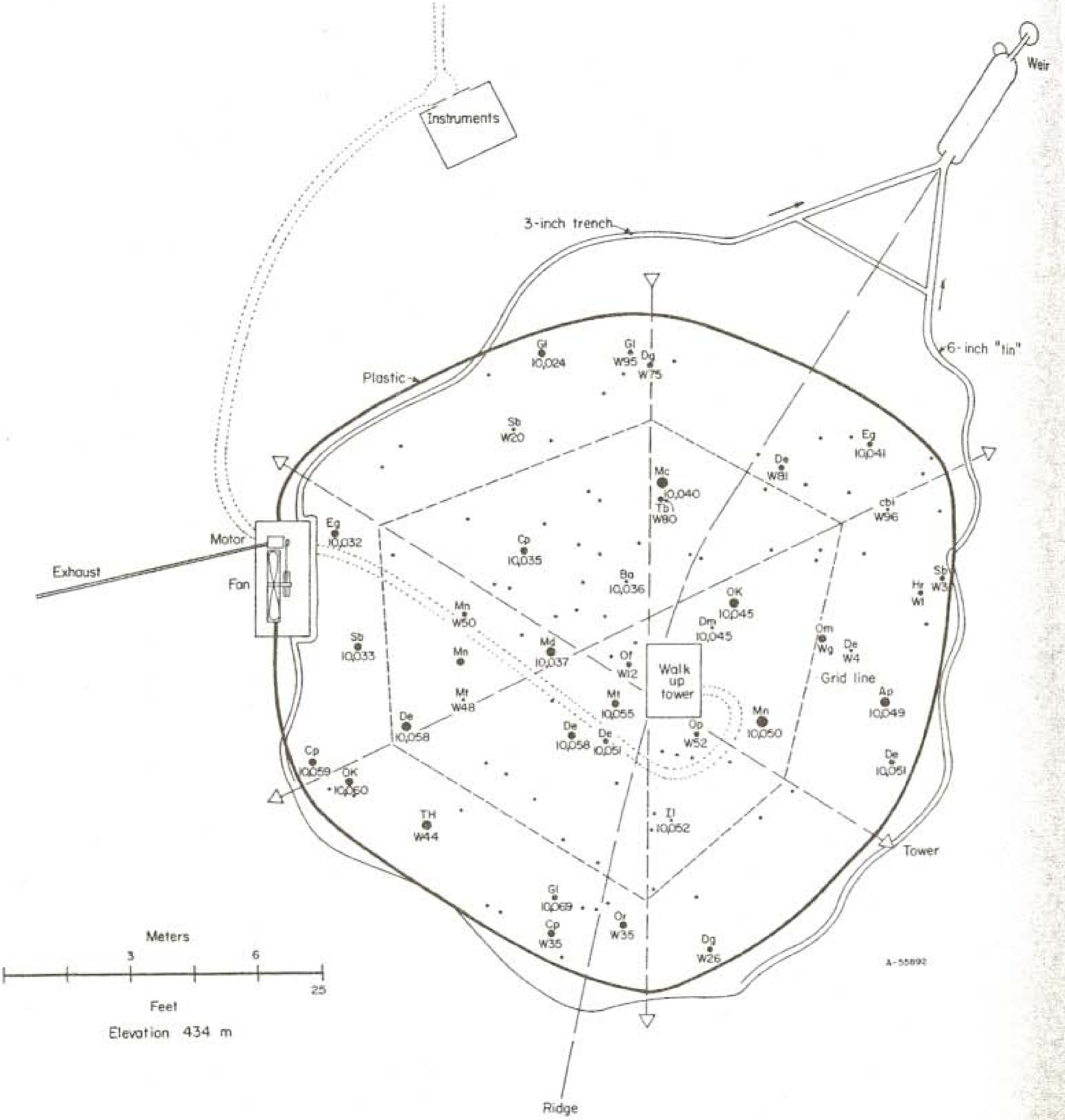

FIGURE 2. MAP OF THE GIANT CYLINDER SITE INCLUDING THE TREES, THE TOWERS, THE COLLECTING TRENCH, AND THE METAL GUARD

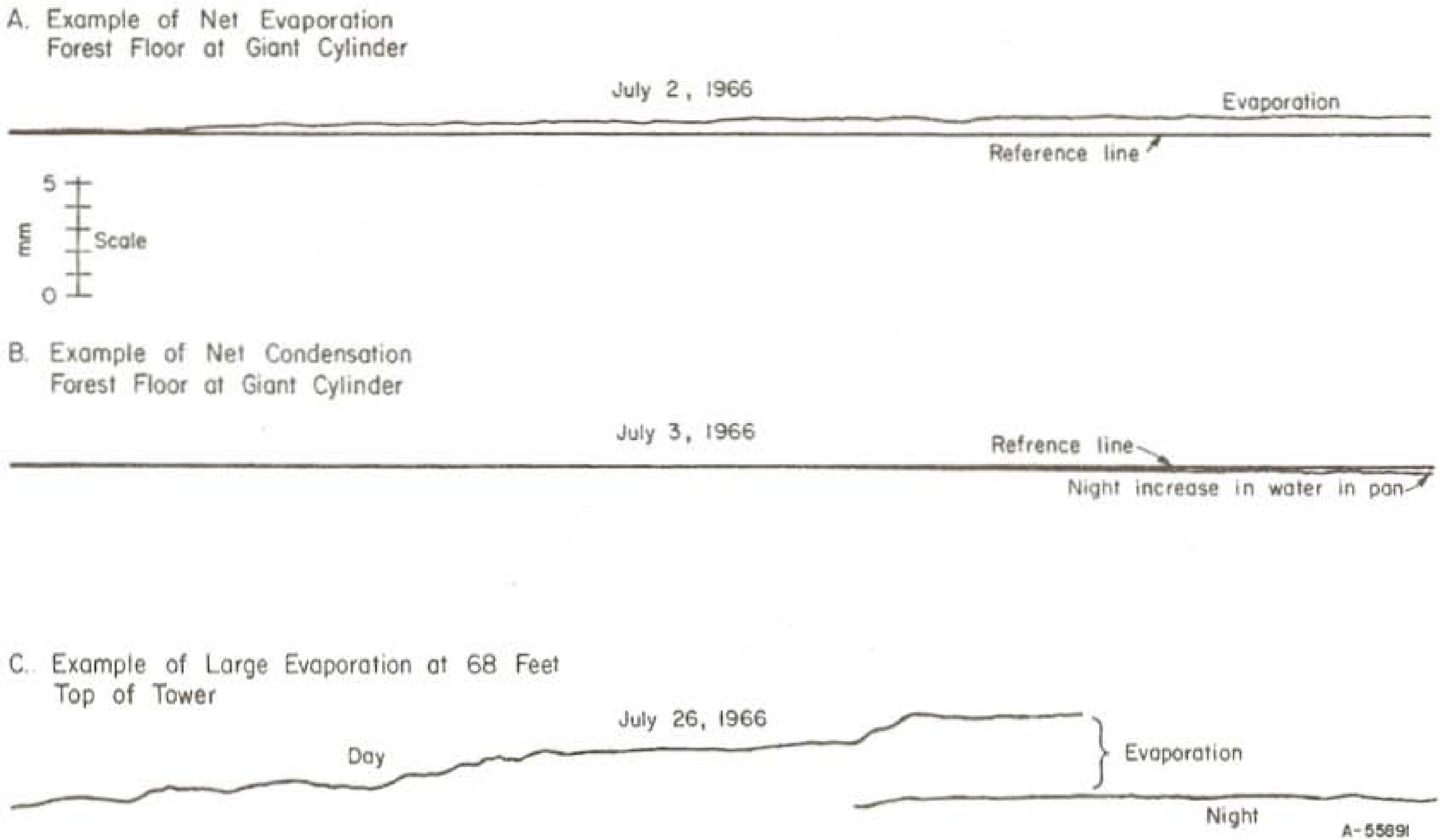

FIGURE 3. EXAMPLES OF DAILY EVAPORATION RECORDS FROM THE EPIC PAN RECORDER ON THE FOREST FLOOR

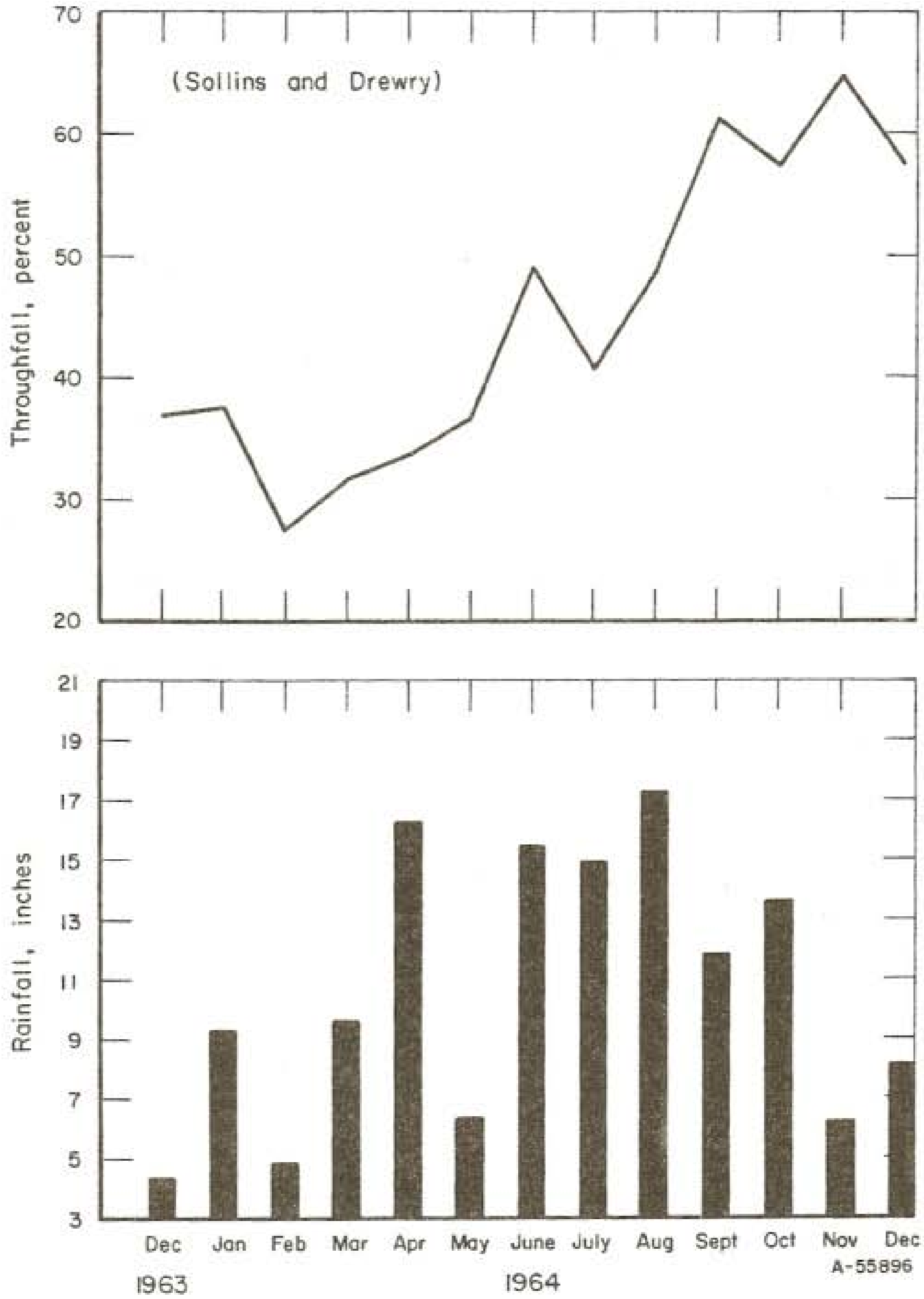

FIGURE 4. RAINFALL AND THROUGHFALL AT A STATION UNDER A MANILKARA BIDENTATA TREE WITHIN THE RAIN FOREST AT EL VERDE

From Sollins and Drewry (Chapter in rain-forest-book manuscript).

The products of the percent throughfall and the rain for that month when summed and divided by the total rain (137.7 inches) give an average throughfall for the year of 41.6 percent.

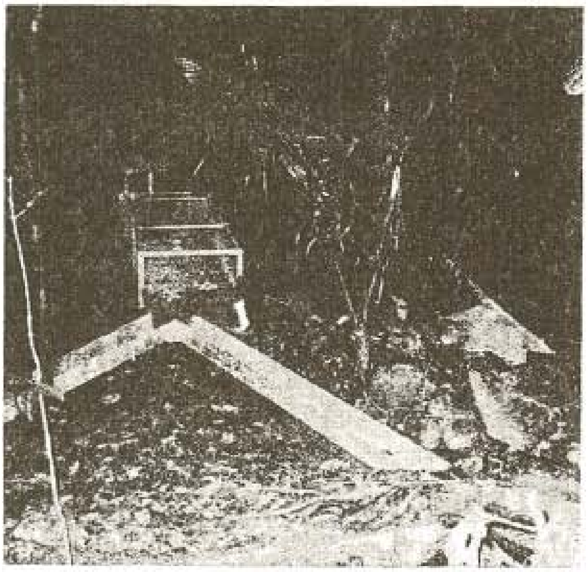

FIGURE 5. VIEW OF WEIR AT THE GIANT CYLINDER SITE

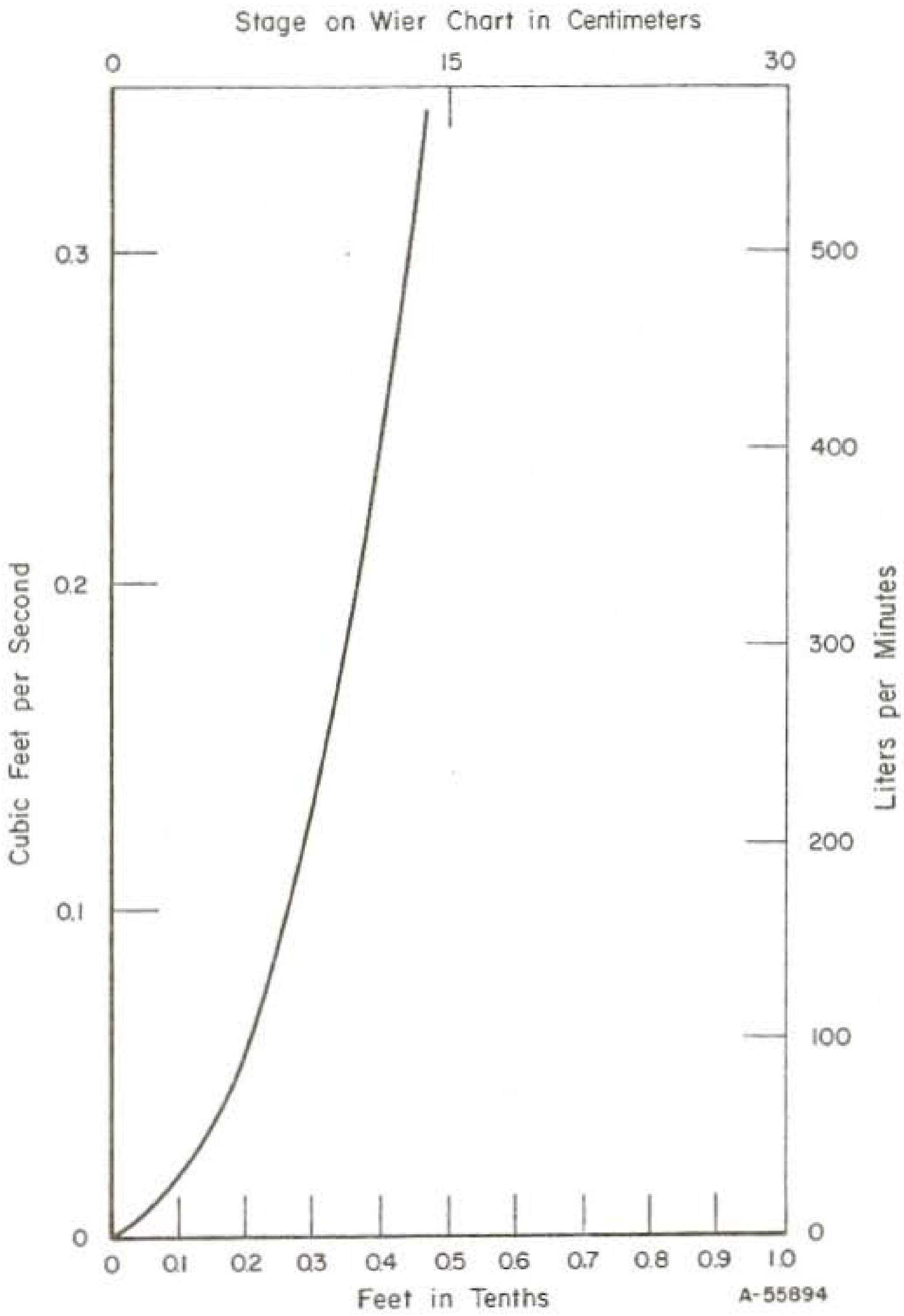

FIGURE 6. GRAPH OF DISCHARGE RATE VERSUS STAGE FOR THE H FLUME AT THE GIANT CYLINDER SITE

Plotted from Holtan, Minshall, and Harrold, 1962.

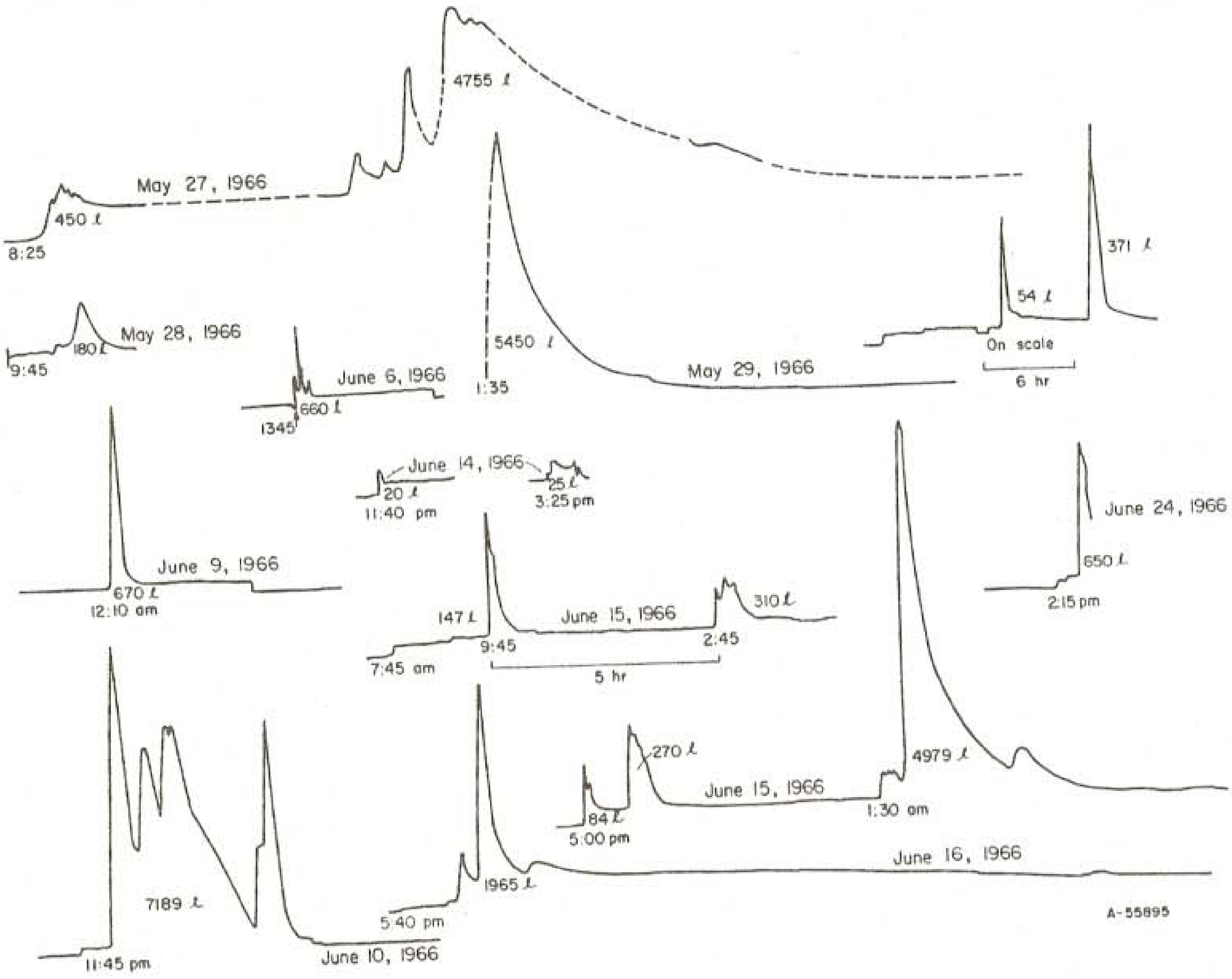

FIGURE 7. FLUME RECORDS DURING JUNE, 1966

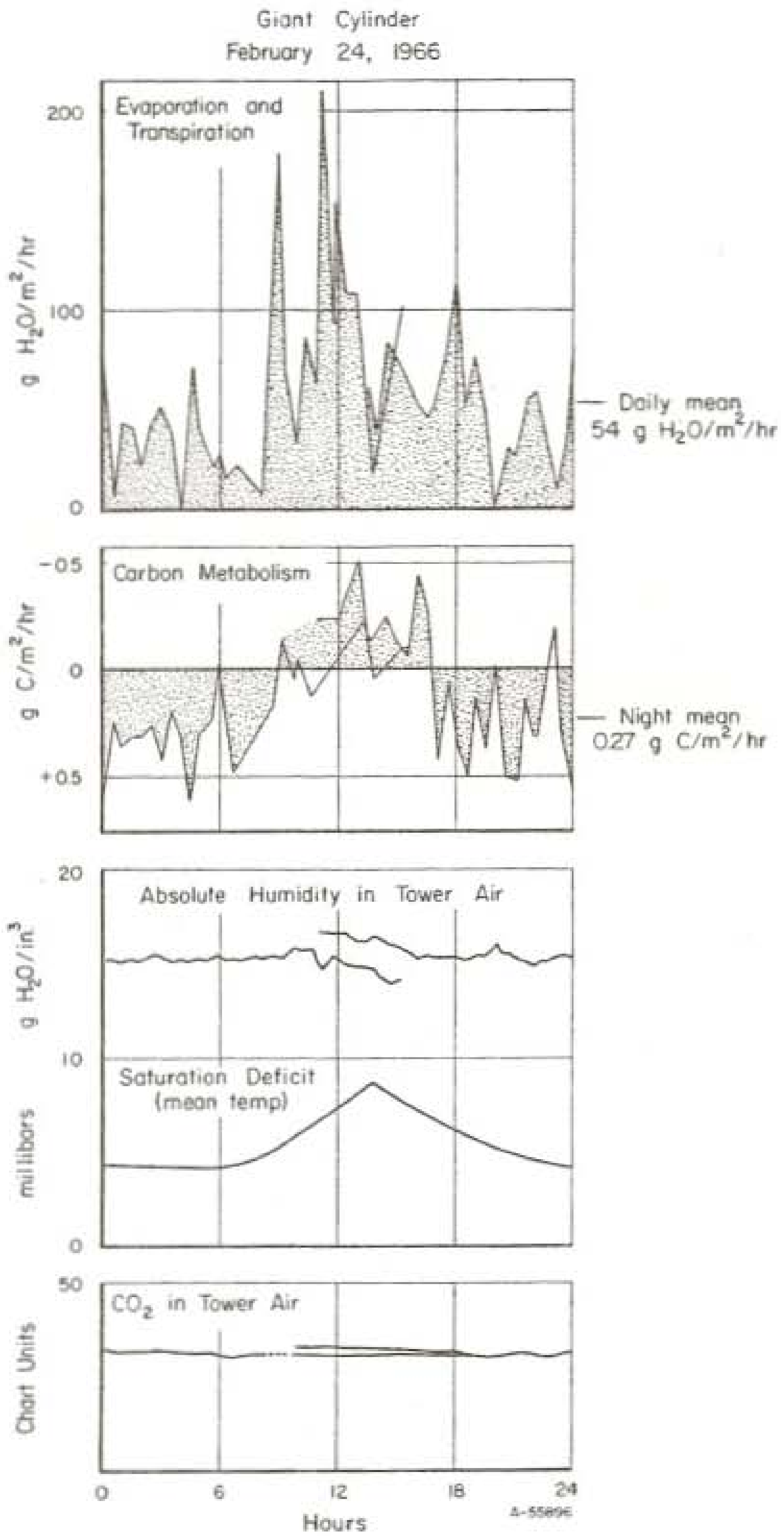

FIGURE 8. RESULTS OF GIANT CYLINDER EXPERIMENT DURING A RELATIVELY DRY PERIOD, FEBRUARY 24, 1966

For details see chapter in the rain-forest-book manuscript. These calculations are preliminary.

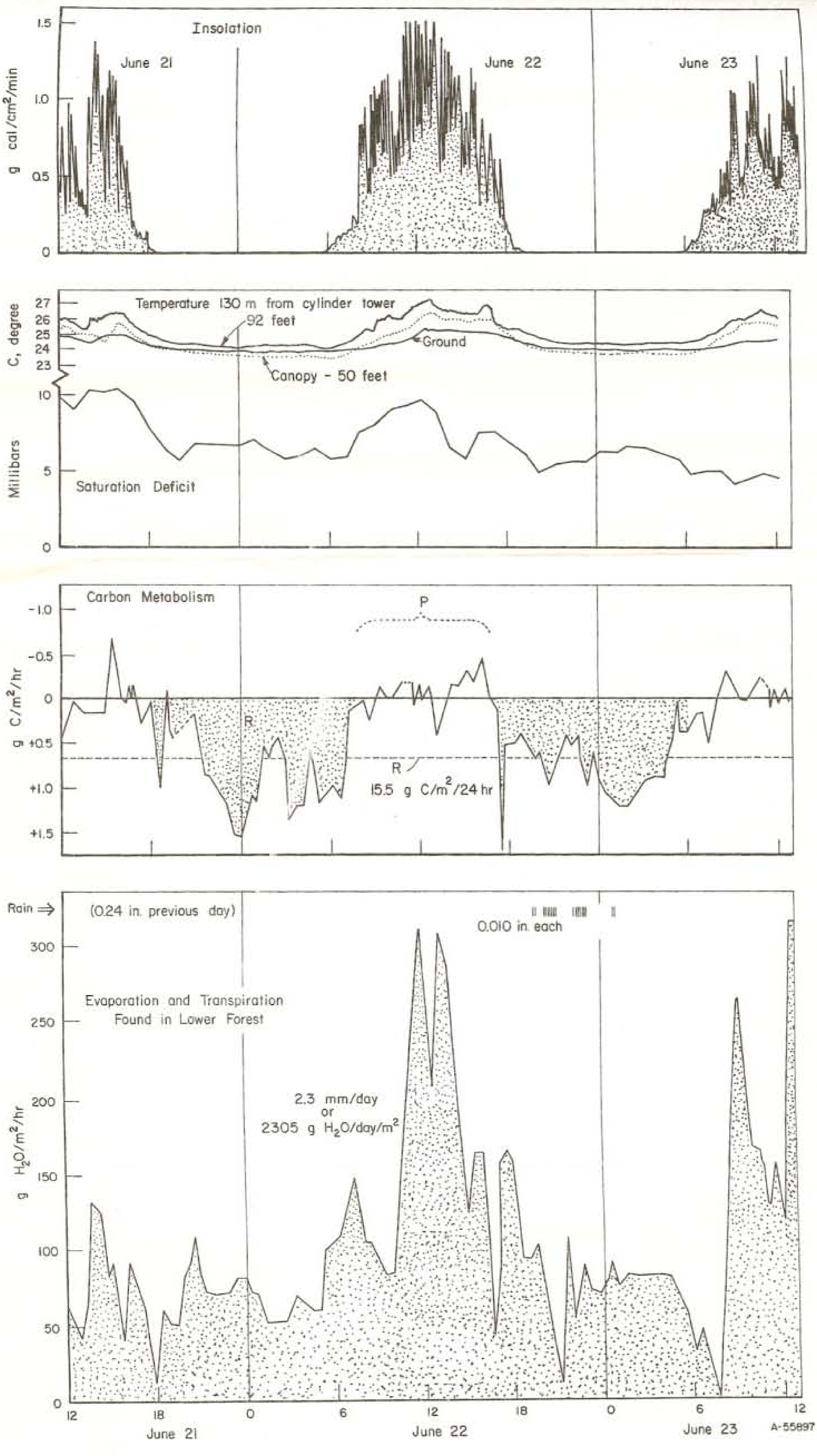

FIGURE 9. RESULTS OF GIANT CYLINDER EXPERIMENT DURING A REGULAR WET PERIOD, JUNE 21 TO 23, 1966

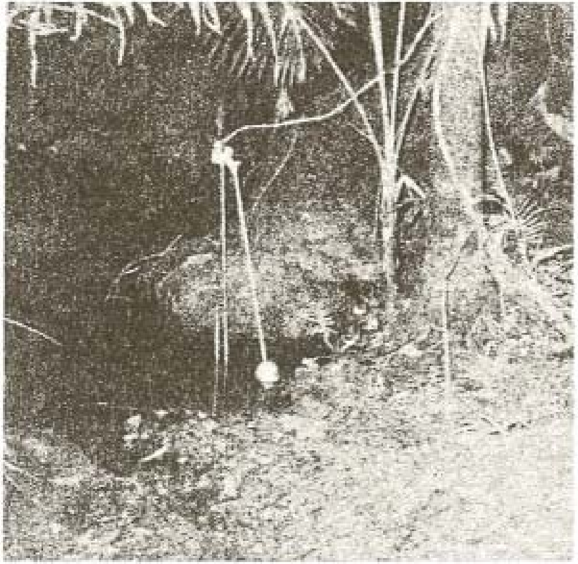

FIGURE 10. VIEW OF THE FLOAT TRANSDUCER ON THE PERMANENT-FLOWING BROOK BELOW THE CYLINDER SITE

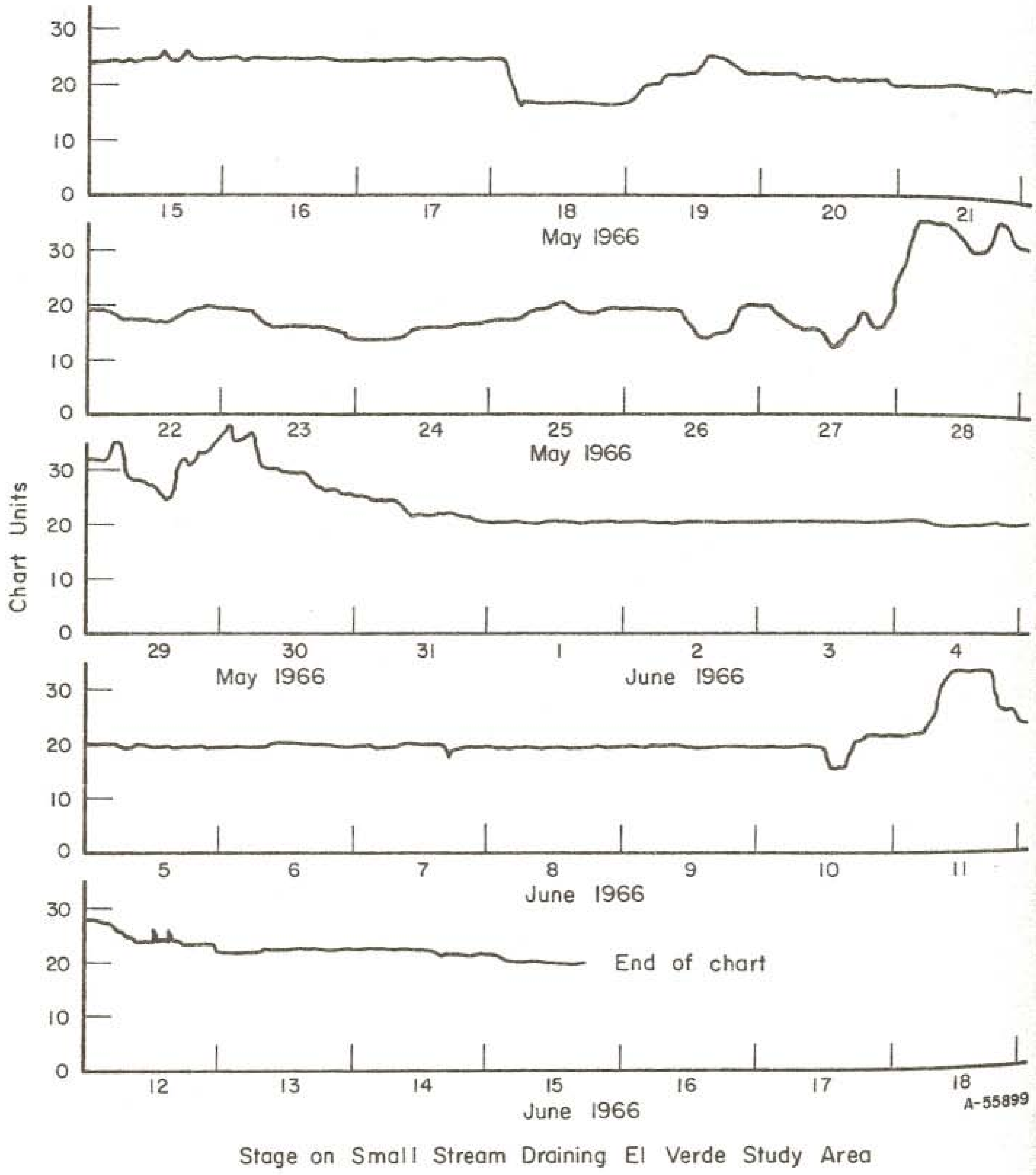

FIGURE 11. TIME RECORD OF WATER LEVEL FROM THE FLOAT (FIGURE 10) IN THE PERMANENT BROOK AT EL VERDE BELOW THE CYLINDER SITE

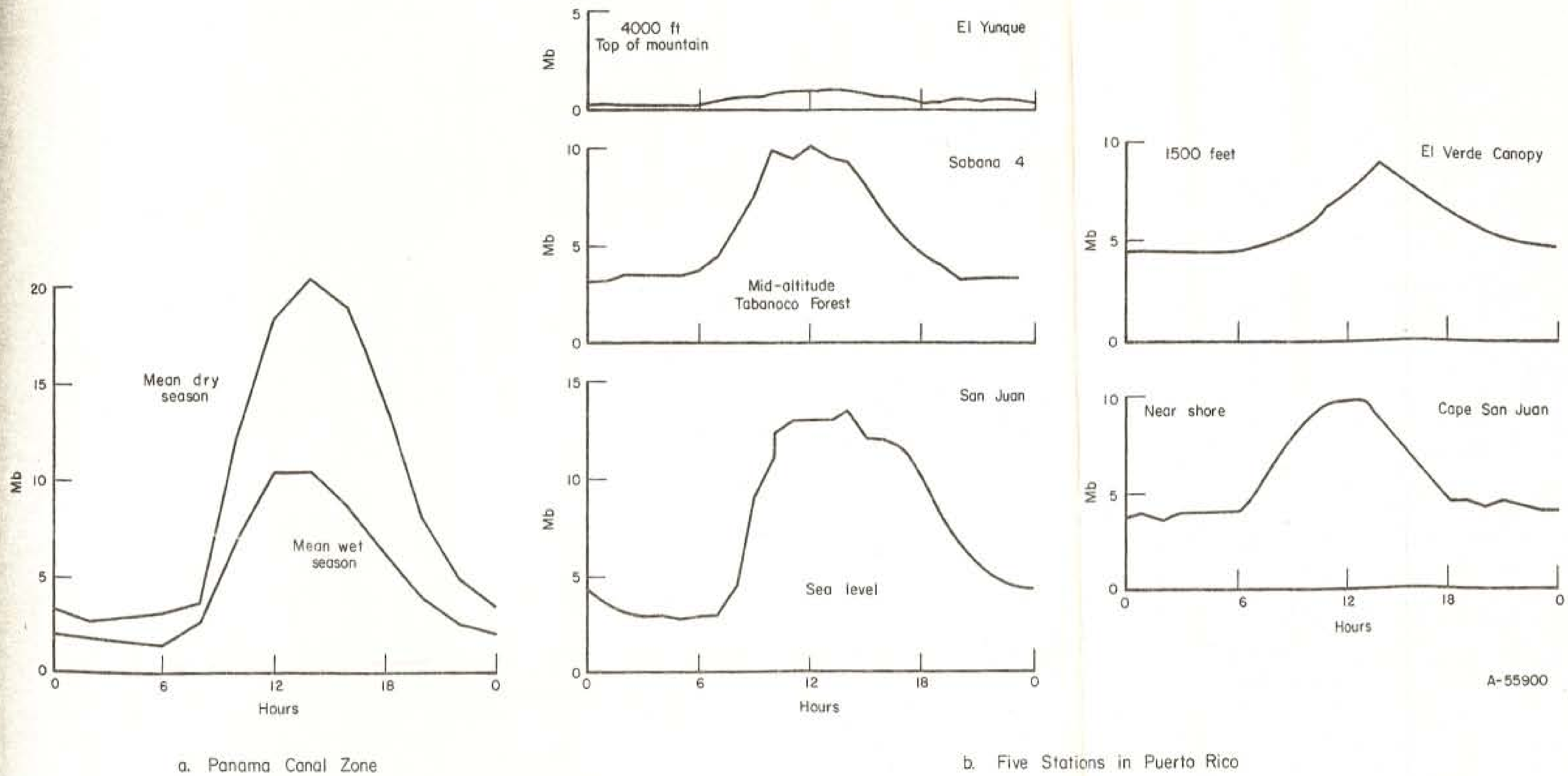

FIGURE 12. DIURNAL PATTERNS OF SATURATION DEFICITS CALCULATED FROM MEAN VALUES FOR TEMPERATURE AND RELATIVE HUMIDITY AT VARIOUS HOURS OF THE DAY

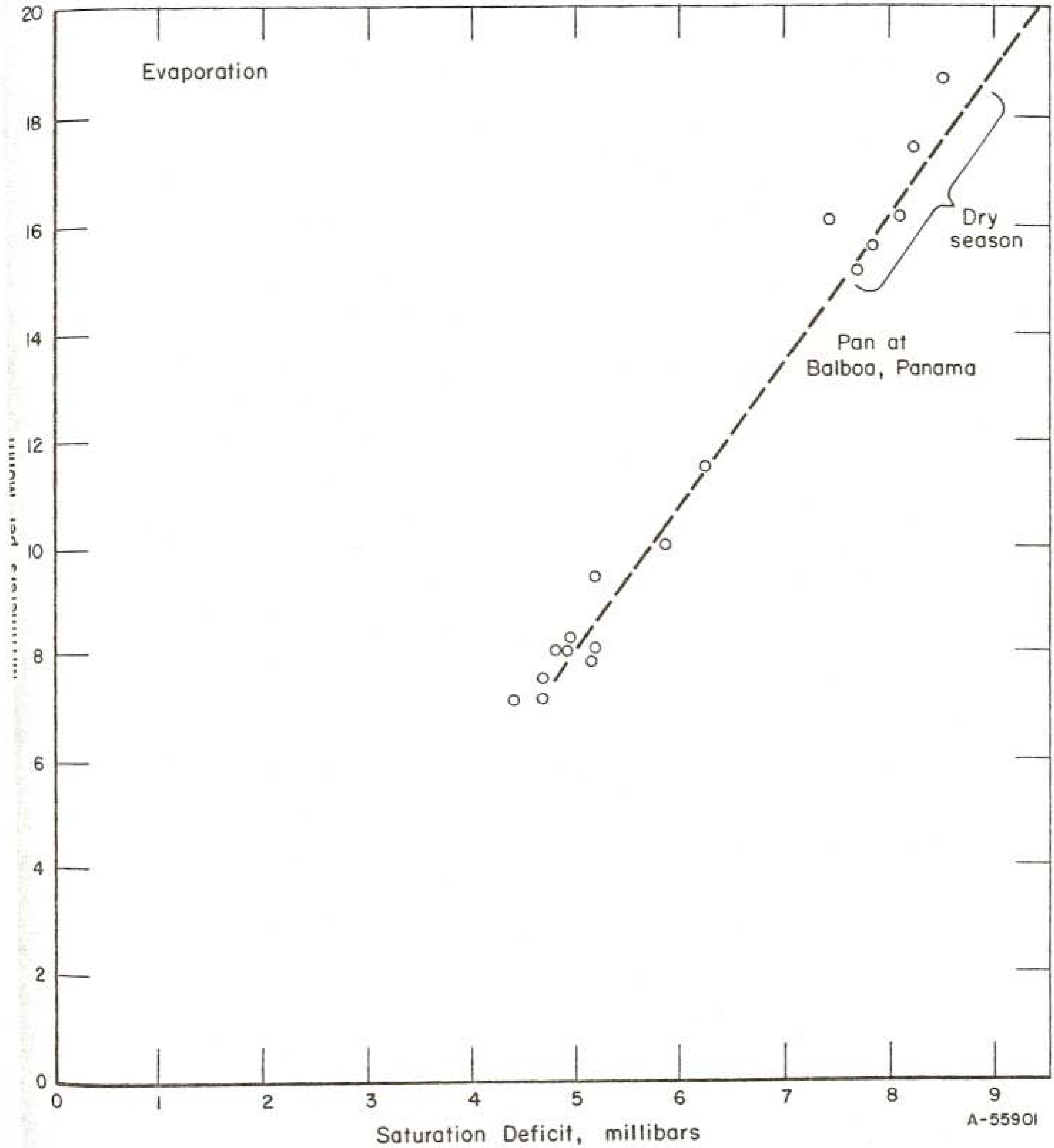

FIGURE 13. PAN EVAPORATION AS A FUNCTION OF SATURATION DEFICIT AT BALBOA, CANAL ZONE

Points are monthly means from Crum (1941).

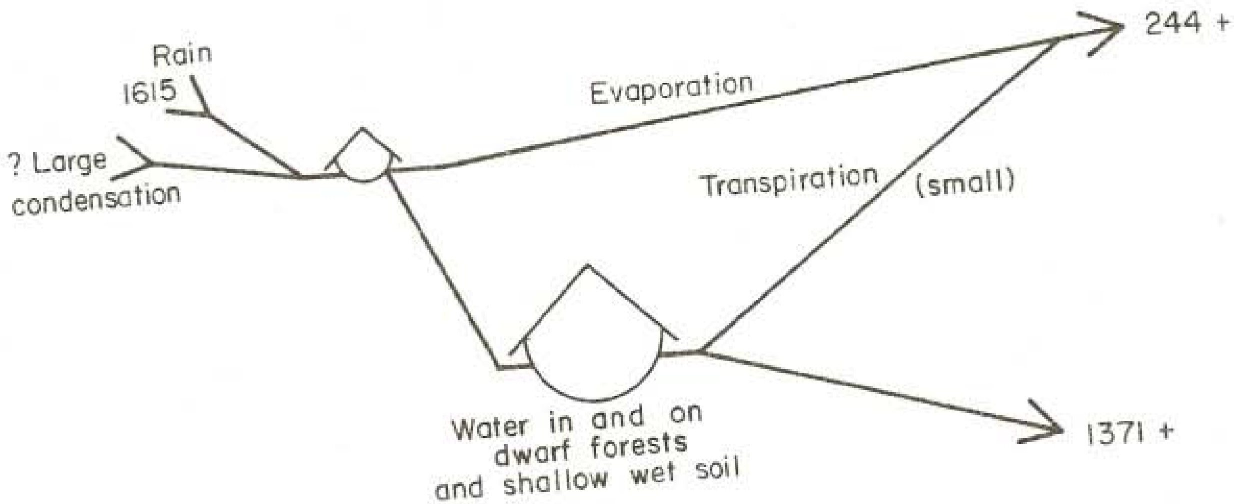

FIGURE 14. WATER BUDGET FROM THE HIGH, CLOUD-SHROUDED ELEVATIONS IN PUERTO RICO

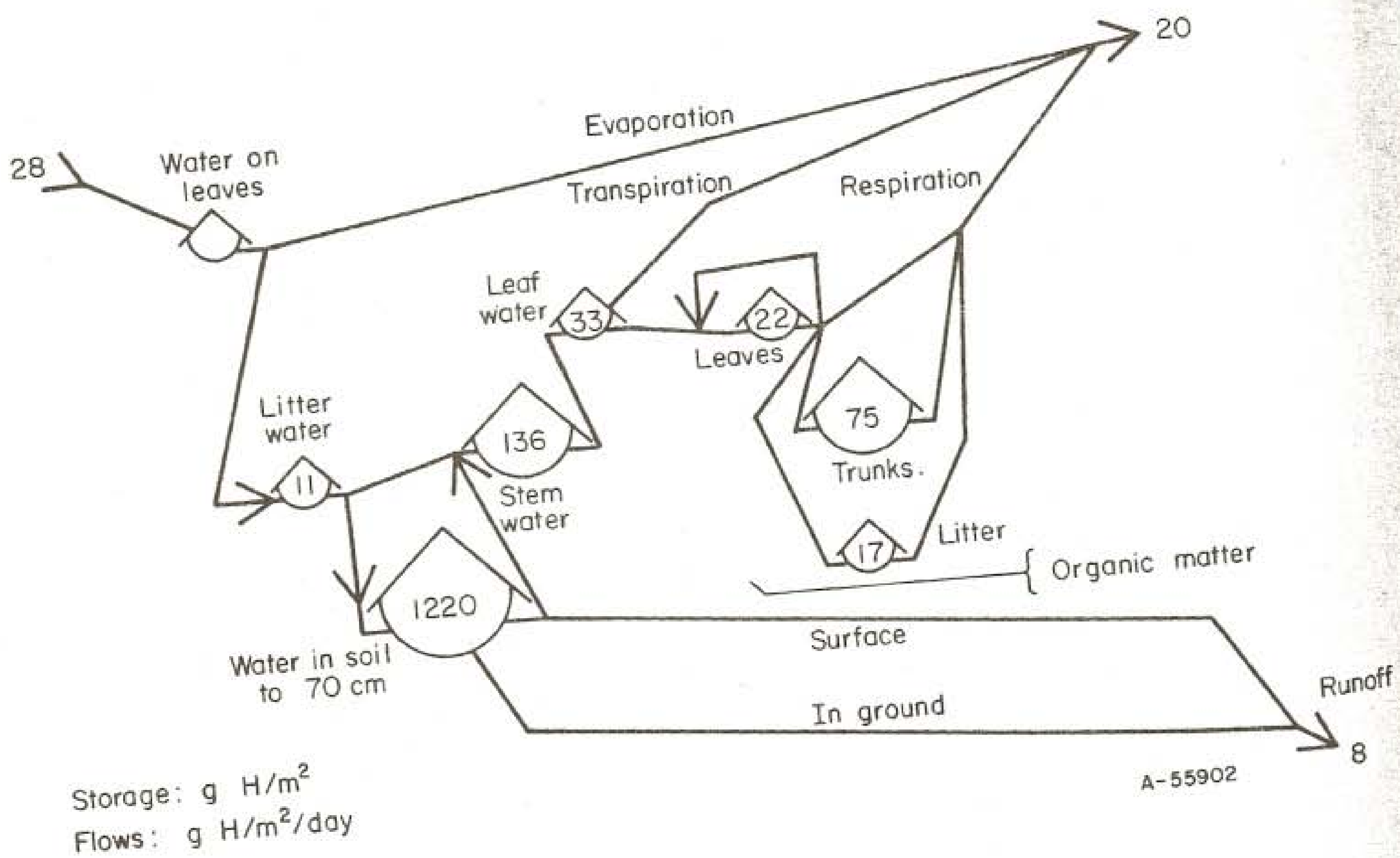

FIGURE 15. WATER BUDGET OF AN ENGLISH WOODLAND PLANTATION

APPENDIX A

MATHEMATICAL FORMULATION OF THE HYDROGEN BUDGET MODEL

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MATHEMATICAL FORMULATION OF THE HYDROGEN BUDGET MODEL

by

Sanford G. Bloom

A simple mathematical formulation for the transfer of tritium in a tropical forest can be derived from H. T. Odum's hydrogen compartmental diagram for the El Verde Rain Forest. Figure A-1 is based on Odum's diagram and is the basis for the present mathematical formulation. A minor feedback was omitted from his compartmental diagram so that an analytical solution could be obtained more easily. The quantities concerned in this feedback are very small and the results should not be significantly affected by this omission.

If it is assumed that the hydrogen flowing into a compartment is completely mixed with the hydrogen within the compartment, the following material balance can be written for each compartment:

$$F_i X_{in} - F_i X_i = A_i \frac{dXi}{dt} + \lambda_D A_i X_i \qquad \text{(A-1)}$$

In - Out = Accumulation + Radioactive Decay

where

F_i is the hydrogen flow rate from Compartment i, $gH/m^2/day$

X_{in} is the tritium concentration of the hydrogen flow into Compartment i, $gH^3/(gH^3+gH^1)$

X_i is the concentration of tritium within Compartment i

A_i is the hydrogen capacity of Compartment i, gH/m^2

t is time, days

λ_D is the radioactive decay rate for tritium or 1.549×10^{-4} $(days)^{-1}$

and i is a subscript used to denote each compartment and has the following values:

i = 0 is leaf surfaces

i = 1 is water in litter-root layer

i = 2 is water in wood

i = 3 is water in clay

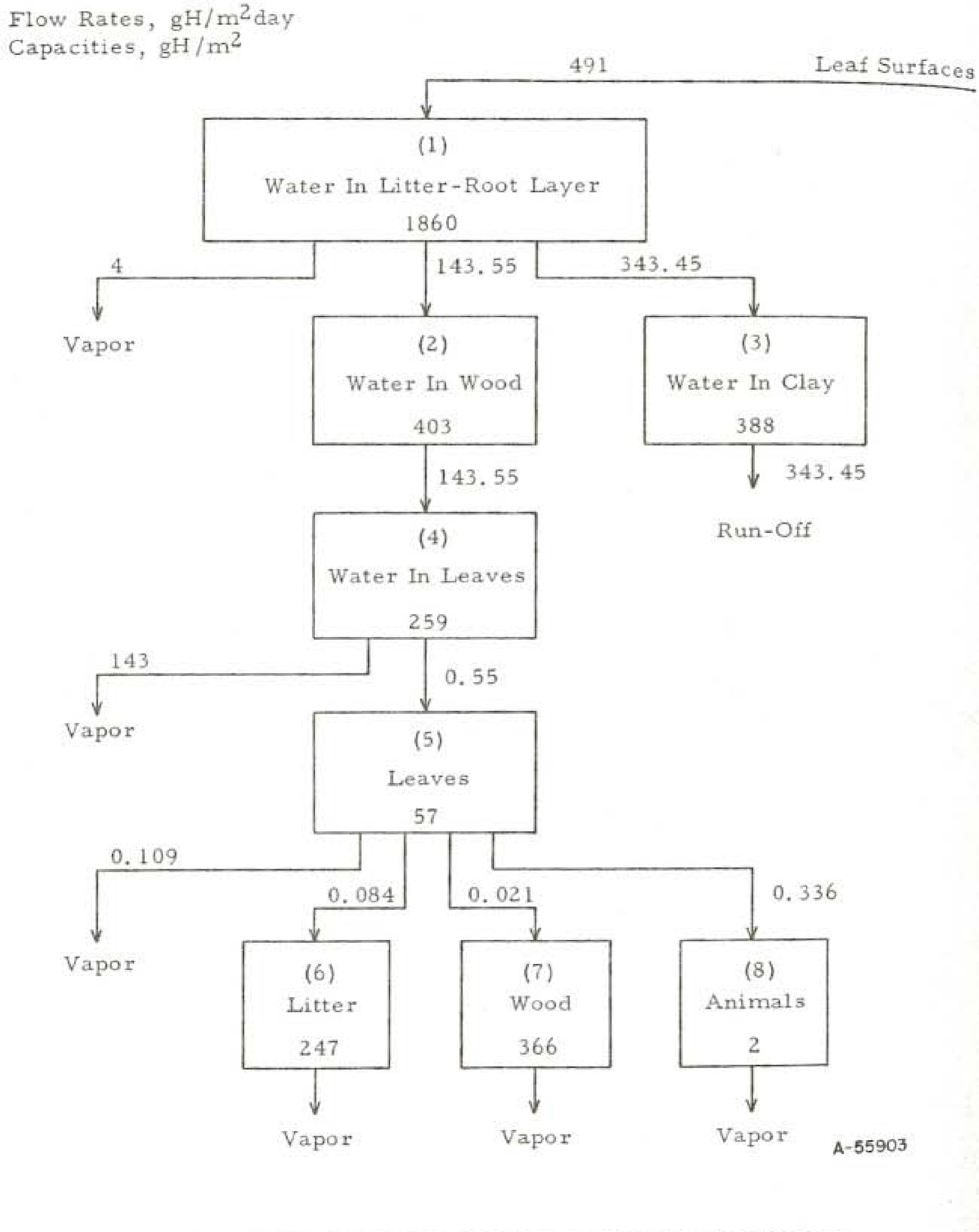

FIGURE A-1. HYDROGEN MODEL FOR EL VERDE RAIN FOREST

$i = 4$ is water in leaves

$i = 5$ is carbohydrates in leaves

$i = 6$ is carbohydrates in litter

$i = 7$ is carbohydrates in wood

$i = 8$ is carbohydrates in animals.

The concentration of tritium in the water on leaf surfaces is taken as a known source term. Since the leaf surfaces have practically no capacity for hydrogen (zero capacity is indicated by Odum's diagram), the tritium concentration in the water from the surfaces would be the same as the concentration in the water raining or condensing onto the surfaces. With X_0 as the source term, Equation (A-1) has the following solution which can be verified by differentiation:

$$X_i = \exp\left(-(\lambda_D + \frac{Fi}{Ai})t\right)\left[Ki + \frac{Fi}{Ai} \int_0^t X_{in}(r) \exp\left((\lambda_D + \frac{Fi}{Ai})r\right) dr\right] \quad . \quad (A-2)$$

where

K_i is the initial tritium concentration in Compartment i.

If X_0 is taken as a pulse equivalent to one $\frac{gH^3\ day}{gH^3 + gH^1}$ at zero time and all other initial concentrations are zero, Equation (A-2) has the following expanded form:

$$X_1 = b_1 \exp(-a_1 t)$$

$$X_2 = b_1 b_2 \left[\frac{\exp(-a_1 t)}{a_2 - a_1} + \frac{\exp(-a_2 t)}{a_1 - a_2} \right]$$

$$X_3 = b_1 b_3 \left[\frac{\exp(-a_1 t)}{a_3 - a_1} + \frac{\exp(-a_3 t)}{a_1 - a_3} \right]$$

$$X_4 = b_1 b_2 b_4 \left[\frac{\exp(-a_1 t)}{(a_4 - a_1)(a_2 - a_1)} + \frac{\exp(-a_2 t)}{(a_4 - a_2)(a_1 - a_2)} + \frac{\exp(-a_4 t)}{(a_1 - a_4)(a_2 - a_4)} \right]$$

$$X_5 = b_1 b_2 b_4 b_5 \left[\frac{\exp(-a_1 t)}{(a_5 - a_1)(a_4 - a_1)(a_2 - a_1)} + \frac{\exp(-a_2 t)}{(a_5 - a_2)(a_4 - a_2)(a_1 - a_2)} + \frac{\exp(-a_4 t)}{(a_5 - a_4)(a_2 - a_4)(a_1 - a_4)} + \frac{\exp(-a_5 t)}{(a_4 - a_5)(a_2 - a_5)(a_1 - a_5)} \right]$$

$$X_6 = b_1 b_2 b_4 b_5 b_6 \left[\frac{\exp(-a_1 t)}{(a_6 - a_1)(a_5 - a_1)(a_4 - a_1)(a_2 - a_1)} + \frac{\exp(-a_2 t)}{(a_6 - a_2)(a_5 - a_2)(a_4 - a_2)(a_1 - a_2)} + \frac{\exp(-a_4 t)}{(a_6 - a_4)(a_5 - a_4)(a_2 - a_4)(a_1 - a_4)} + \frac{\exp(-a_5 t)}{(a_6 - a_5)(a_4 - a_5)(a_2 - a_5)(a_1 - a_5)} + \frac{\exp(-a_6 t)}{(a_5 - a_6)(a_4 - a_6)(a_2 - a_6)(a_1 - a_6)} \right] , \quad \text{(A-3)}$$

where

$$bi = Fi/A_i$$

and

$$a_i = \lambda_D + b_i \quad .$$

The expressions for X_7 and X_8 are identical to the expression for X_6 except the corresponding values of a_7 and b_7 or a_8 and b_8 replace a_6 and b_6.

The expressions for X_1 through X_8 have been evaluated and the results are shown in Figure A-2. The values of F and A, as well as the derived values of a and b which were used to evaluate the expressions, are given in Table A-1. In using Figure A-2,

TABLE A-1. VALUES OF CONSTANTS USED IN THE HYDROGEN MODEL

i	F	A	a	b
1	491	1860	0.2641333	0.2640
2	143.55	403	0.3561102	0.3562
3	343.45	388	0.8853353	0.8852
4	143.55	259	0.5544020	0.5542
5	0.55	57	0.0098040	0.009649
6	0.084	247	0.00049498	0.0003401
7	0.021	366	0.000212277	0.00005738
8	0.336	2	0.1681549	0.1680

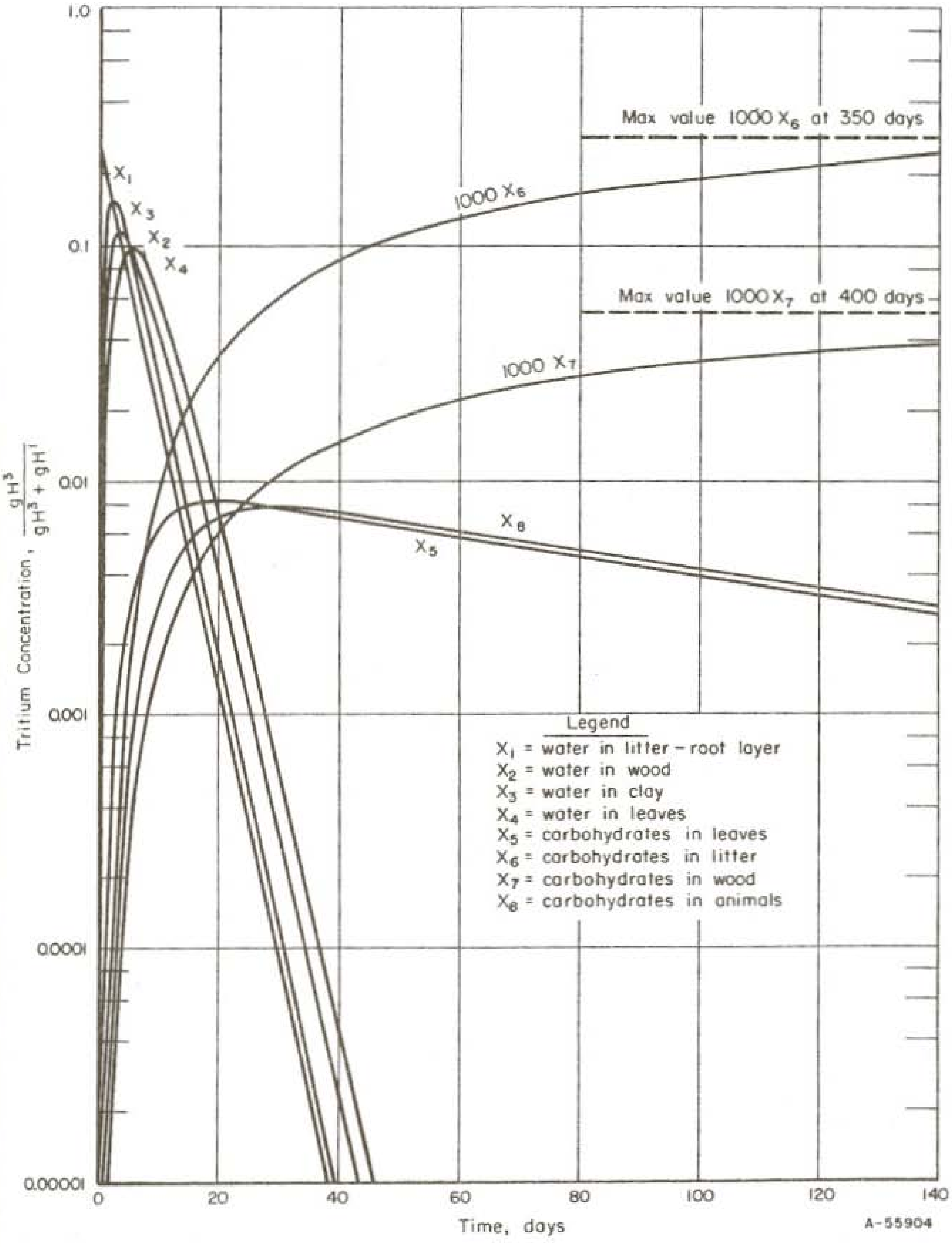

FIGURE A-2. RESPONSE OF HYDROGEN MODEL TO A UNIT PULSE OF TRITIUM any convenient units may be used for tritium concentration provided the same units are used in all compartments. Also, if the pulse concentration of X_0 is not unity but m unit the resulting values of X_1 through X_8 are merely the product of m and the values from Figure A-2. For example, if the pulse concentration of X_0 is $\frac{3CiH^3 day}{gH}$, then the corresponding values for X_1 through X_8 at 20 days are approximately 4×10^{-3}, 1×10^{-2}, 6×10^{-3}, 2×10^{-3}, 2×10^{-3}, 9×10^{-5}, 2×10^{-5}, and $2 \times 10^{-3} \frac{CiH^3}{gH}$.

From Figure A-2, it can be seen that the tritium concentrations in the water compartments are initially high but decay very rapidly. The tritium concentrations in the other compartments are not very high but they decay very slowly and are therefore the items of concern for long periods of time. The slow decay rates of these latter compartments are due to the slow hydrogen flow, and therefore the low elimination rate, from the compartments.