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ON THE PHYSICAL AND CHEMICAL PROPERTIES OF THROUGHFALL AND STEMFLOW

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SYNOPSIS

The effect of vegetation on the physical and chemical characteristics of rainwater that is delivered to the soil is investigated through observations of 13 rainfall events for a watershed with deciduous and coniferous vegetation. Lumped characteristics of the resulting throughfall (ThF) and stemflow (SF) are analyzed in comparison with rainfall characteristics. Certain factors, such as the species and size of trees for stemflow and the distance from the stem for throughfall, were also investigated to determine their relationships to the quantity and quality of SF and ThF. To check the observed data, a tank model is used to model SF and ThF rates and concentrations. Results show that 71% of the rainfall becomes ThF and that the SF rate is 22 times that of the rainfall rate. It was also found that SF rate and the quality were highly dependent on the tree type. Due to the characteristics of the basin, ThF is found to be independent of tree characteristics. Finally the tank model is found to be sufficiently capable of modeling SF and ThF rates and quality.

INTRODUCTION

Most present day models of water flow through the soil utilize rainfall quantity and quality as direct inputs to the soil system. However, it is a known fact that for forested basins, vegetation intercepts rainfall and this in turn delivers it to the soil. If the effects of vegetation on the intensity, quality and time of delivery of the rain water that infiltrates the soil are negligible, then we can generally ignore the effect.

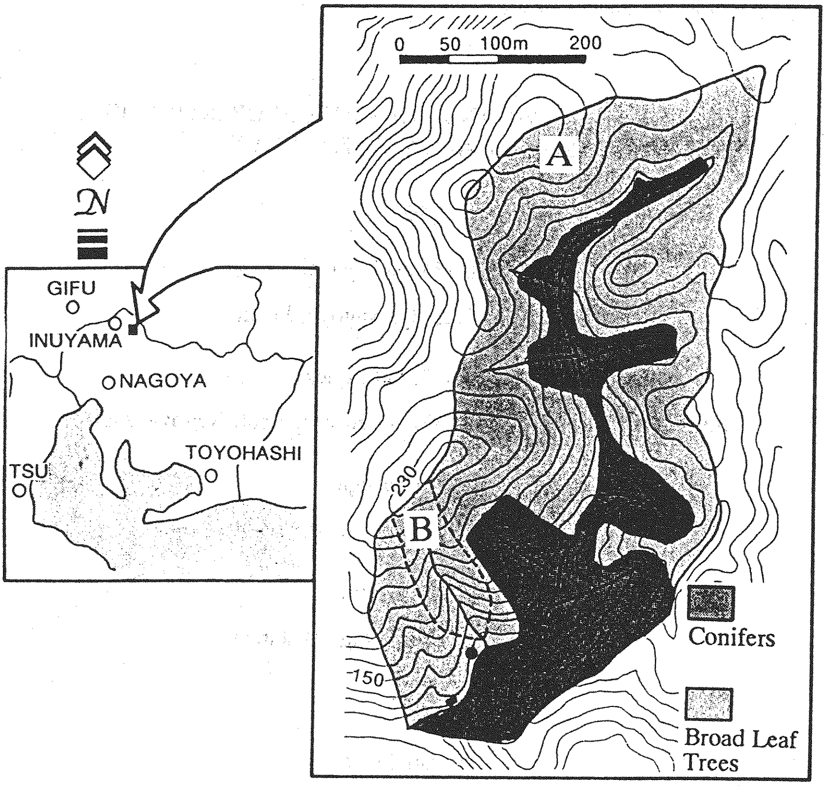


Figure 1. Location of Study Basin

However, since it has been reported that vegetation affects rainfall quality (Rodà et al. 1990, Lelong et al. 1990) and more importantly intensity (Brown and Barker 1970, Johnson 1990, Hashino et al. 1991,1992, Sakamoto and Murota 1992), then these effects obviously cannot be neglected, especially in event flow modeling. However, until now, there has been no definitive study of the physical and chemical effects of basin vegetation on water that infiltrates the soil. Because of this, it would be desirable to study how stemflow and throughfall are affected by canopy interception of rainfall. This research determines the effects of vegetation on the physical and chemical properties of rainfall delivered to the soil.

STUDY AREA

The basins studied in this research are located in Inuyama City in Aichi Prefecture. The basin areas are 171,000 m^2 for basin A and 8800 m^2 for basin B. The vegetation map of the basins can be seen in Figure 1. At higher elevations, the vegetation consists of broad leaf trees (Oak, Mountain Cherry, Camellia, Hackberry and Wisteria). At lower elevations of basin A and in the front-most (easily accessible) part of the watershed, the vegetation is mostly conifers (Cedar and Pine). Most of the observations made in this research are taken from basin B where the vegetation is deciduous or broad leaf-type.

PHYSICAL AND CHEMICAL PROPERTIES OF STEMFLOW AND THROUGHFALL

Information on the water budget for the forest canopy is very important especially for modeling

Table 1. Summary of stemflow and throughfall data. Here SF1 to SF7 are stemflow sampling points and ThF1 to ThF4 are throughfall sampling points.

(1-a)	Vegetation				SF/r				C_{SF}/C_r [pH_{SF}/pH_r], ave. of hourly ratios	
	Tree	Trunk Dia (cm)	Inclination(Deg)	Foliage Ht (m)	6/23/92	7/11/92	7/17/92	9/29/92	6/29/93 - 7/2/93	7/3/93 - 7/4/93
Stemflow 1 (SF1)	Mountain Cherry Tree	22.9	32.2	13.0	16.806	21.13	18.74	26.18	1.131 [0.828]	0.994 [0.769]
Stemflow 2 (SF2)	Mountain Cherry Tree	20.7	33.6	12.0	14.482	0.0	25.87	6.95	1.417 [0.760]	0.971 [0.680]
Stemflow 3 (SF3)	Mountain Cherry Tree	21.0	24.6	12.8	12.503	15.6	20.73	15.18	2.120 [0.808]	1.961 [0.739]
Stemflow 4 (SF4)	Camellia	8.3	0	6.1	5.4349	5.9	11.63	2.57	1.323 [1.001]	1.414 [0.935]
Stemflow 7 (SF7)	Oak	9.2	0	3.0	29.736	23.95	29.0	28.62	1.152 [0.937]	0.841 [0.842]

(1-b)	Vegetation			Event Through-fall (mm) [$ThF/r]_{total}$		ThF/r, average of hourly ratios		C_{ThF}/C_r [pH_{ThF}/pH_r], average of hourly ratios	
	Kind	Trunk Diam. (cm)	Distance From Collector (m)	6/29/93 - 7/2/93	7/3/93 - 7/3/93	6/29/93 - 7/2/93	7/3/93 - 7/3/93	6/29/93 - 7/2/93	7/3/93 - 7/3/93
Throughfall 1 (ThF1)	Mountain Cherry Tree	22.9	1.0	58.3 [0.61]	27.3 [0.65]	0.754	0.767	1.102 [1.015]	1.351 [0.938]
Throughfall 2 (ThF2)	Mountain Cherry Tree	22.9	0.8	76.9 [.81]	34.7 [0.83]	1.081	0.989	1.266 [0.853]	1.319 [0.951]
Throughfall 3	Oak	9.0	0.8	72.7	33.9	0.919	0.983	1.236	1.2
(ThF3)	Oak	9.0	0.8	[0.76]	[0.81]			[1.016]	[0.940]
	Hackberry	34.0	1.5						
Throughfall 4	Camellia	9.0	1.1	84.0	39.9	1.146	1.119	0.951	1.169
(ThF4)	Oak	55.0	1.9	[0.88]	[0.95]			[1.001]	[0.952]

rainfall infiltration and tracer transport through the soil. Lelong et al. (1990), Rodà et al. (1990) and Sakamoto and Murota (1992) have found that as the forest canopy converts rainfall into stemflow and throughfall, this affects the quality and rate of water delivered to the soil. Moreover, Hashino et al. (1991, 1992) have shown that the water balance of these canopy components can be adequately described using tank models of varying complexities. Presently, more information is required on the changes that occur in rainfall intensity and concentration between the canopy and the soil. In this research, it is intended to model the stemflow and throughfall components using a simple tank model whose properties are derived from the observed characteristics of these components. Through this modeling, basic parameters that govern the chemical and physical processes of vegetation interception will be derived.

Stemflow and throughfall rates and water samples were collected from Basin B during the period of June 1992 to October 1993, comprising 13 rainfall events. To measure stemflow, collar-like devices similar to those from Voight (1960) were attached about 1 meter from the base of the trees. These collectors divert water into automatic tipping bucket gauges of different sizes, depending on the size of the tree. Five stemflow collectors were used (See Table 1-a). Rectangular and circular collectors were placed at different positions and distances from trees to measure throughfall. The throughfall summary can be seen in Table 1-b. with Stemflow and throughfall data for one rainfall event are given in Figure 2. Here the graphs represent, from the top, rainfall intensity, stream water chemograph and hydrograph, rainfall chemograph, stemflow1 chemograph, and hourly-average throughfall intensity and chemograph, respectively.

From Figure 2, it can be seen that throughfall is more responsive to rainfall chemistry changes than stemflow, which shows lesser fluctuations both in conductivity values and pH. This may be due to the relatively shorter contact time between the rainwater and the leaves for throughfall compared with stemflow. Another possible reason is a difference in leaching rates of certain ions that contribute to the conductivity of throughfall and stemflow.

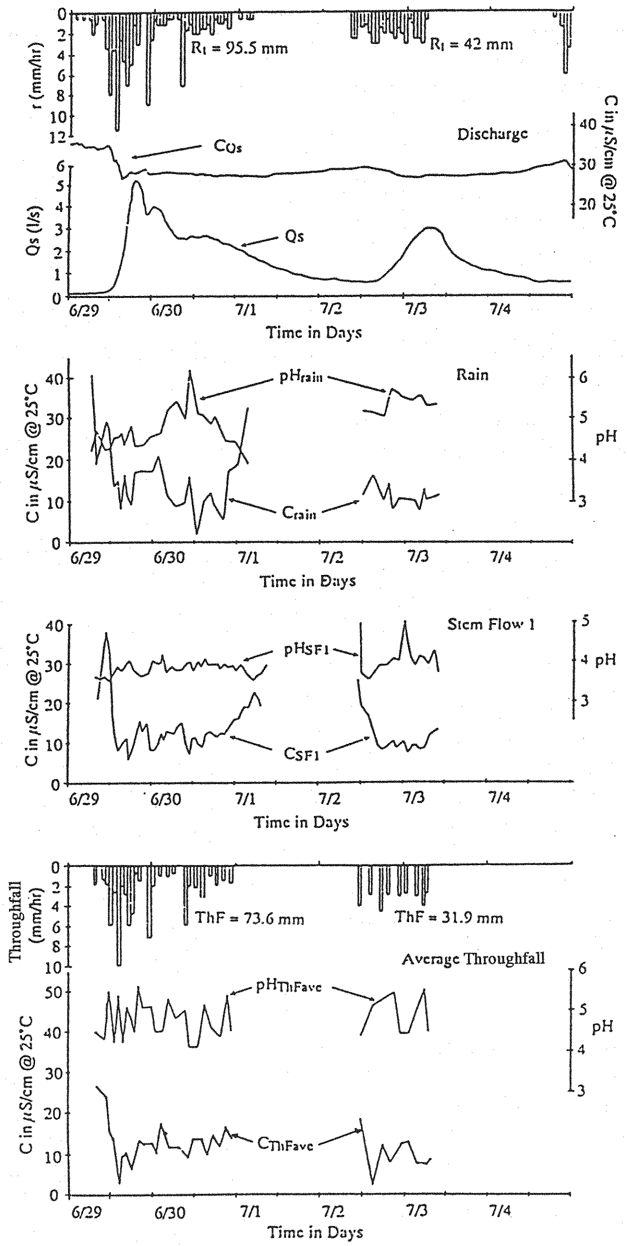


Figure 2. (From the top) Rainfall intensity, streamwater chemograph and hydrograph, stemflow 1 chemograph, and hourly average throughfall rate and chemograph for the rainfall event of June 29, 1993 to July 4, 1993.

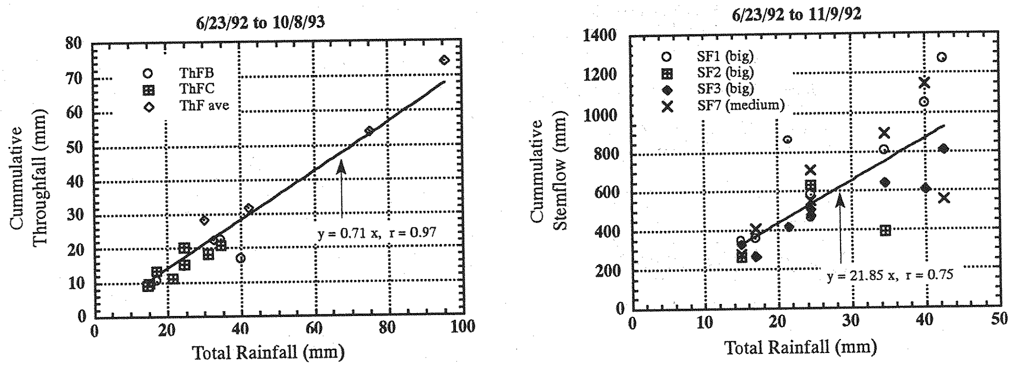


Figure 3. Lumped throughfall and stemflow versus rainfall for 13 rainfall events from June 1992 to October 1993.

To determine the relationships between stemflow, throughfall and rainfall, we plotted the total rainfall against cumulative stemflow and throughfall (See Figure 3). In this Figure, *ThFB* and *ThFC* are from data observed in 1992, while ThF_{ave} are average throughfall data for four events listed in Table 1-b (*ThF1* to *ThF4* denote sampling points). Also *SF1* to *SF7* denote sampling points as described in Table 1-a. The stemflow rates are computed using 'effective tree flow area', which is the assumed area in the soil where a particular stemflow of a tree infiltrates the soil, and are estimated from paint tests mentioned later.

Lumped Characteristics Of Throughfall

Initially we investigated the characteristics of throughfall irrespective of the distance from the nearest tree, or tree type. The observations were carried out on trees whose foliage more or less completely intercepts rainfall as indicated by a lack of open areas under canopies.

Figure 3 shows a close relationship between throughfall and rainfall (r=0.97). According to the figure, 71 percent of the total rainfall during an event was distributed as throughfall. For the area covered with conifers in the watershed, observations showed that this ratio is almost 78 percent. This may be attributed to the fact that conifers have narrower foliage and smaller branches than the broad leaf trees. These data may be compared to those of Brown and Parker (1970) from a basin covered with oak. Their observation showed that 85 percent of the gross rainfall becomes throughfall during the dormant season (periods when the trees have less or no leaves) and 83 percent for the growing season (with leaves). Although our observations in this research covers most of the rainy season, the autumn and winter seasons are not covered due to a lack of considerable rainfall. However, Brown and Parker (1970) showed that throughfall was not significantly different between trees of a single group or between seasons. Also, Helvey and Patric (1965) showed that throughfall is independent of tree age, although Johnson (1990) reported that this may not be the case for the same tree groups located in different basins.

Lumped Characteristics Of Stemflow

One of the most difficult assumptions to be made when determining stemflow is the computation of the effective stemflow area. This is because stemflow needs to be converted from volume measurements into a unit of water depth. In this research, we utilized a simple paint test to determine the tree flow area for different tree categories. First we divided the trees into 3 categories according to trunk diameters,

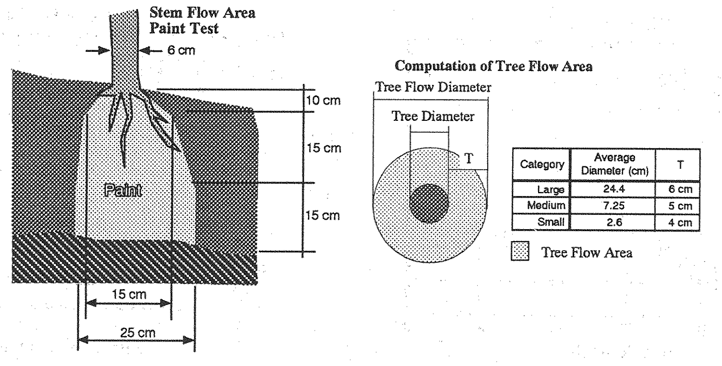


Figure 4. Field experiment to determine the tree flow area for stem flow.

namely; large, medium and small. The tree flow areas were then computed at a depth of ten centimeters below the ground surface level (See Figure 4). For the large trees (diameters greater than 12 centimeters), a flow area consisting of a ring 6 centimeters wide around the tree was observed. For medium trees (5 to 12 centimeters in diameter), the ring width was found to be 5 centimeters, and for small trees (less than 5 centimeters in diameter), the width was 4 centimeters. Using these observations, the stemflow rates were computed shown in Figure 3. This figure shows a wide variation of data points about a fitting line, with a regression coefficient of 0.75. This is because we assumed a constant value for the ring diameter, T, for each tree category. Since there is a great variability of the actual tree flow areas in the field, the smaller trees in each category become sensitive to the assumed ring diameter. The observed value of 6 centimeters maybe too big for the large tree category as these showed the most scatter in the plot. Back solving, it was found that to obtain a regression coefficient of 0.9, a ring width of 5.8 centimeters (instead of 6 centimeters) should be used for the large tree category. However, since these are only arbitrary values, these assumptions were acceptable. The results of this regression suggest that the typical stemflow rate is about 22 times that of rainfall intensity. This large value may be explained by the fact that stemflow was being concentrated on a small infiltration area compared to the rain.

Factors Affecting Stem Flow And Throughfall Characteristics

The above discussions are for lumped systems, which means that they are values for all the sampling points irrespective of the tree type or category for stemflow, and the distance from the nearest tree for throughfall. To determine the effects of these factors, we also summarized data for each sampling point including these information. This is summarized in Table 1, which also includes chemical ratios of the stemflow and throughfall with rainfall per collector. The information in Table 1 suggests that stemflow rate is independent of the tree-size. It also shows that throughfall rate is independent of the distance of the collector from the nearest tree. These results agree with those reported by Brown and Parker (1970) and Helvey and Patric (1965) which showed that throughfall and stemflow do not depend on the size or age of trees within a single group. As for the chemical characteristics of stemflow and throughfall, Table 1 shows that canopy interactions produced throughfall and stemflow having a conductivity greater than rainfall. This can be seen in the consistently high electrical conductivity ratios of stemflow to rainfall. The results for pH show that the stemflow produces consistently more acidic flows while throughfall is less acidic. These results agree with those observed by Rodà et al. (1990) in a holm-oak forest in NE Spain.

The effect of the tree type and the distance of the throughfall collector from the tree are also investigated. From the data collected and shown in Table 1, it has been found that the stemflow characteristics

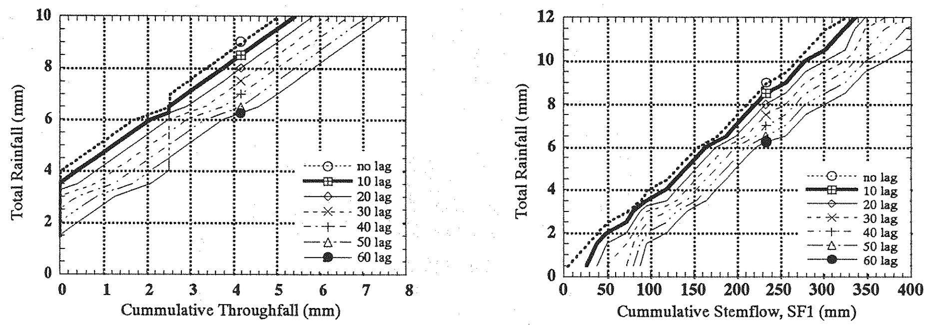


Figure 5. Total rain versus cummulative ThF and SF plots to determine the average lag responses of these components.

is tree kind dependent with flows being more acidic for mountain Cherry trees compared to Oaks or Camellias. It was also found that throughfall quality and quantity is independent of the distance of the collector from the nearest tree. This may be attributed to the fact that the observation points are thickly covered with overlapping canopies thus removing the actual effects of the thinning of the canopy with increasing distance from the tree trunk. Generally however, Johnson (1990) has shown that there is a tendency for throughfall to increase as the distance of the collector from the tree stem increases.

Checking Observations Using Tank Model

Another important problem to be considered is the dynamic characteristics of stemflow, SF, and throughfall, ThF, in particular with regard to the storage capacity of the trees and the time lag of delivery of rainwater to the soil. To determine the average time lag of the SF and ThF, total rainfall is plotted against the cumulative SF and ThF for varying lagged responses (See Figure 5). These relationships show the average response time of both stemflow and throughfall. In Figure 5, it can be seen that the best linear relationships occurs with a 10 minute lag for both ThF and SF. This indicates that the rainwater has a considerable residence time in the leaves as compared with the stem. These results are reasonable because of the differences in the physical shapes and orientations of the leaves that produce throughfall and the tree trunk and branches which produce stemflow.

From the above observations, a tank model was used to simulate the effects of vegetation interception on the quantity and quality of water delivered to the soil system. Through this kind of analysis, we intend to derive basic chemical and physical parameters which cannot be obtained from static analyses of observed data. The model comprises two tanks in series for all tree groups. This is because of the finding that throughfall and stemflow do not vary significantly for different tree categories. The model is described schematically in Figure 6. In this model, the upper tank simulates canopy interception which distributes rainwater into stemflow and throughfall. The lower tank generates the stemflow component. The upper tank (tank A) has two openings located at a height h_A from the bottom. One of the openings is for throughfall and the other is for input to the stemflow tank. The outflows through these openings are divided by a distribution parameter α. The height h_A is the apparent storage of the foliage which causes a time lag for both stemflow and throughfall during the initial stage of a rainfall event. The depth of tank A is taken to be H_A. This permits overflows during intense rain periods. These are divided into both a stemflow component (tank B) and a throughfall component. The distribution of these overflows is controlled by the parameter β.

The lower tank has a single opening located at a height h_B from the bottom where the tank depth is

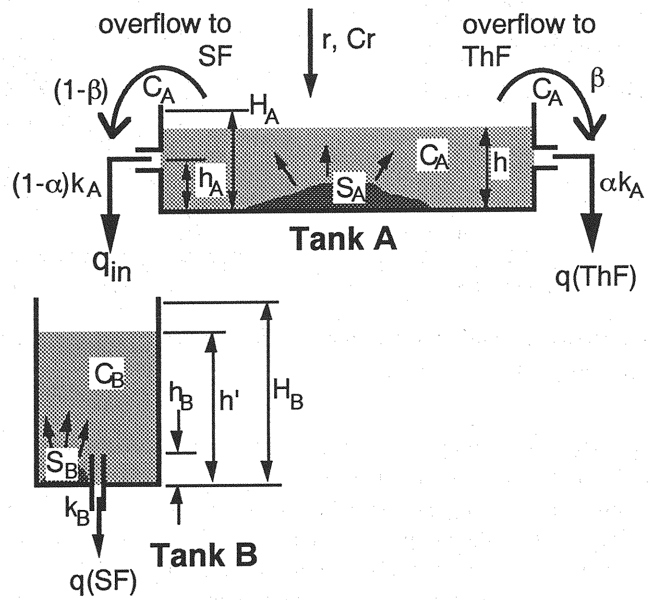


Figure 6. Schematic diagram of the proposed tank model.

assumed to be large enough not to permit overflow. The overflow from this tank is assumed to be technically impossible because of the physical orientation of the tree stem. The input to this tank is from the combined outflow from an opening and overflow from tank A.

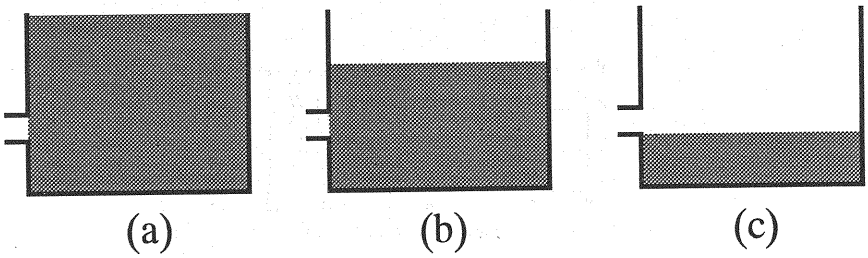
Both tanks have three possible states; a) the tank is full, outflow occurs from the openings and there may be overflow, b) the water level is below the brim but above the openings and there is flow from the openings but no overflow, and c) the water is below the level of the openings and there is no outflow. If there is no rain at this state, then there is evaporation which empties the tank in 1 day (assuming that during rainfall, evaporation is small). This is schematically shown in Figure 7.

The equations of continuity and drainage from tanks A and B for these states are given by equations (1) and (2), where q_{in} is the total input to tank B from tank A which is a combination of the outflow and overflow. The total discharge which becomes throughfall, *q(ThF)*, is a combination of outflow from an opening and overflow from Tank A.

In these equations, k_A and k_B are opening coefficients, w is the average stemflow area per unit forest surface area, and α and β are distribution coefficients for drainage and overflow of tank A, respectively. Since actual data are available for the percentage of throughfall for this basin, the parameters α and β will be computed to correspond to this percentage (71% throughfall, 29% stemflow).

The tanks are initially assumed to be empty, thus equation (3).

To model the change in concentration for stemflow and throughfall, it is assumed that the mass supplied from the vegetation can be expressed by a kinetic approach towards an equilibrium where the mass balance equations and the vegetation supply terms are given by equation (4) where C_A and C_B are the concentrations of the storage in the tanks, C_{Ao} and C_{Bo} are the initial concentrations, C_r is the rainfall concentration, S_A and S_B are the mass supply from vegetation and γ_A and γ_B are kinetic coefficients.



Tank A

$$
(1)\left\{
\begin{array}{l}
\text{a) } \dfrac{\partial h}{\partial t} = 0,\ h = H_A\ ; \\
\qquad q_{in} = k_A(H_A - h_A)(1-\alpha) + \left(r - k_A(H_A - h_A)\right)(1-\beta)\ ; \\
\qquad q(ThF) = \left[k_A(H_A - h_A)\alpha + \left(r - k_A(H_A - h_A)\right)\beta\right]/(1-w) \\
\text{b) } \dfrac{\partial h}{\partial t} = r - k_A(h - h_A)\ ; \\
\qquad q_{in} = k_A(h - h_A)(1-\alpha)\ ;\ q(ThF) = k_A(h - h_A)\alpha/(1-w) \\
\text{c) } \dfrac{\partial h}{\partial t} = \left\{ \begin{array}{ll} r & ; r > 0 \\ -\dfrac{h_A}{1\ \text{day}} & ; r = 0 \end{array} \right. ;\ q_{in} = 0\ ;\ q(ThF) = 0
\end{array}
\right.
$$

Tank B

$$
(2)\left\{
\begin{array}{l}
\text{a') } (H_B = \text{large enough}) \\
\text{b') } \dfrac{\partial h'}{\partial t} = q_{\text{in}} - k_B(h' - h_B)\ ;\quad q(SF) = k_B(h' - h_B)/w \\
\text{c') } \dfrac{\partial h'}{\partial t} = \left\{ \begin{array}{ll} q_{\text{in}} & ; q_{\text{in}} > 0 \\ -\dfrac{h_B}{1\ \text{day}} & ; q_{\text{in}} = 0 \end{array} \right.
\end{array}
\right.
$$

(3) At t=0, h = h' = 0

$$
(4)\left\{
\begin{array}{l}
h\dfrac{\partial C_A}{\partial t} = (C_r - C_A)r + S_A\ ;\ h'\dfrac{\partial C_B}{\partial t} = (C_A - C_B)q_{in} + S_B \\
\text{where, } S_A = \gamma_A(C_{Ao} - C_A)\ ;\ S_B = \gamma_B(C_{Bo} - C_B)
\end{array}
\right.
$$

Figure 7. Schematic diagram of the 3 states of the water level in the tank and the equations of continuity and discharge for tanks A and B, initial condition and mass balance equations for the concentration monitored.

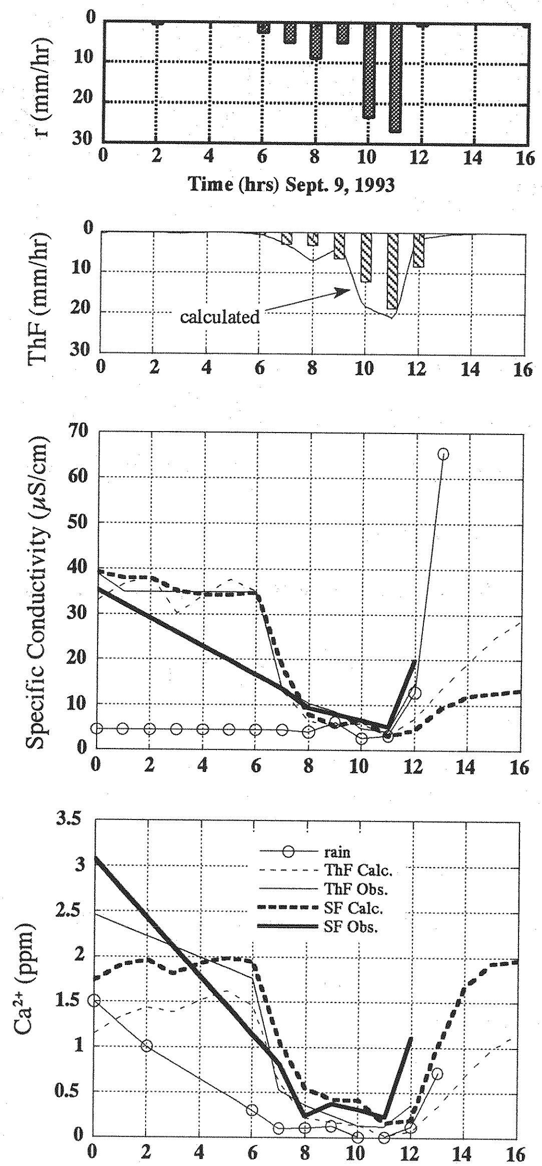


Figure 8. Drainage rate and concentration data computed by the proposed tank model fitted to the observed data of September 9, 1993. From the top: observed rainfall rate; observed and calculated throughfall rate; observed and calculated throughfall and stemflow conductivity; and observed and calculated throughfall and stemflow Ca^{2+} concentration. Parameters: k_A=2.0 (1/hr), k_B=6.0 (1/hr), h_A=1.0 (mm), h_B=0.1 (mm), H_A=2.3 (mm), α=0.75 (-), β=0.9 (-) C_{Ao}=60 (μS/cm) for conductance and 2.0 (ppm) for Ca^{+2}, C_{Bo}=60 (μS/cm) for conductance and 2.0 (ppm) for Ca^{+2}, γ_A=0.15 for C and 0.25 for Ca^{2+} (mm/hr), and γ_B=0.0 for C and 0.18 for Ca^{2+} (mm/hr).

The drainage rates and concentrations computed by the proposed tank model are shown in Figure 8. The graph is for the rainfall event of 9 September 1993. The second graph in Figure 8 shows the observed throughfall rate as the bar graph and the computed ThF rate as the solid line. Both observed (solid lines) and computed (dashed lines) concentrations of throughfall and stemflow are also shown. The parameters h_A and H_A were assumed to be equal to 1 and 2.3 millimeters respectively, to simulate the physical properties of the leaves. The storage height, h_B, for tank B was assumed to be 0.1 millimeters. This was assumed because in Figure 5, both throughfall and stemflow had an apparent time lag of 10 minutes which would mean that water had very little residence time in the stem compared with the leaves. This would mean that there would relatively be a very small storage space in the stem and thus a small value for h_B. The parameter α was assumed to be 0.75 and the parameter β to be 0.9. To obtain a good fit for the concentrations, the mass kinetic parameters, γ_A and γ_B, were found to be 0.15 and 0.0 for conductivity, and 0.25 and 0.18 for Ca^{2+} for tanks A and B respectively. This suggests that the foliage has a greater amount of ions compared with the tree trunk. This can be explained by the large difference in the exposed areas of these two components. Another possibility is that since the present assumption does not permit a direct input of rainfall into the stemflow component, fresh rainwater comes in contact with the leaves first (thus a big reaction towards equilibrium) and then it flows down the stem. As the water is almost in a state of equilibrium there is minimal further reaction.

As can be seen in Figure 8 an acceptable fit of the computed data was obtained for quantity and quality modeling. However, since this event lacked stemflow rate data, no fitting was made on this quantity. Using the same parameters for different rainfall events with stemflow rate data produced good fitting curves. Additional problems include (a) quantifying the parameter α and β; (b) the possibility that rainfall may directly enter tank B without first being intercepted by tank A; and (c) the possibility of a variable mass source function for different kinds of chemicals used as tracer. Although a great deal of improvement can still be made in terms of model development, it has been clearly shown that observed physical characteristics of throughfall and stemflow can be used to improve the modeling of the processes involved especially with respect to the chemical properties of water.

CONCLUSIONS

This research investigates the effect of vegetation on the physical and chemical characteristics of rainwater that is delivered to the soil, based on observations of 13 rainfall events for a basin containing deciduous and coniferous vegetation. Characteristics of throughfall and stemflow were analyzed in conjunction with rainfall characteristics. Other factors, such as tree type and the distance from the stem were also investigated to determine their effect on the quantity and quality of SF and ThF. To check the observed data, a tank model is used to describe SF and ThF rates and concentrations.

Results shows that (a) 71% of the rainfall becomes ThF and that the SF rate is 22 times that of the rainfall rate. (b) It was also found that SF is highly dependent on the tree type both for the rate and the quality. (c) Due to the characteristics of the basin, ThF is found to be independent of tree characteristics. (d) Finally a tank model was found to be sufficiently capable of modeling SF and ThF rate and quality, which can give us an indication of physical and chemical properties of the vegetation interception process.

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APPENDIX - NOTATION

The following symbols are used in this paper:

α = Distribution parameter for the opening of tank A (–);
β = Distribution parameter for the overflow from tank A (–);
C = Specific electrical conductivity (μS/cm);
C_r = Concentration of the rainfall (μS/cm mm/hr for C and ppm mm/hr for Ca^{2+});
C_A = Concentration of the water in tank A (μS/cm mm/hr for C and ppm mm/hr for Ca^{2+});
C_{Ao} = Initial concentration of the water in tank A (μS/cm mm/hr for C and ppm mm/hr for Ca^{2+});
C_B = Concentration of the water in tank B (μS/cm mm/hr for C and ppm mm/hr for Ca^{2+});
C_{Bo} = Initial concentration of the water in tank B (μS/cm mm/hr for C and ppm mm/hr for Ca^{2+});
h = Height of water in tank A (mm);
h' = Height of water in tank B (mm);
h_A = Height of midpoint of opening from the bottom of tank A (mm);
h_B = Height of midpoint of opening from the bottom of tank B (mm);
H_A = Height of tank A (mm);
H_B = Height of tank B (mm);
k_A = Orifice coefficient for tank A ($hour^{-1}$);
k_B = Orifice coefficient for tank B ($hour^{-1}$);
q = Outflow from tank A (mm/hr);
q_{in} = Stemflow component of the outflow from tank A (mm/hr);
q(ThF) = Throughfall component of the outflow from tank A (mm/hr);
q(SF) = Outflow from tank B (mm/hr);
Q_s = Discharge in basin B (liters/sec);
r = Rainfall intensity (mm/hr);
R_t = Total rainfall (mm);
S_A = Constant supply of mass from vegetation in tank A (μS/cm mm/hr for C and ppm mm/hr for Ca^{2+});
S_B = Constant supply of mass from vegetation in tank B (μS/cm mm/hr for C and ppm mm/hr

for Ca^{2+});

SF	=	Stemflow (mm);
ThF	=	Throughfall (mm);
w	=	The average stemflow area per unit forest surface area (m^2/m^2);
1-w	=	The average throughfall area per unit forest surface area (m^2/m^2);
γA	=	kinetic parameter for the supply of mass from vegetation in tank A (mm/hr); and
γB	=	kinetic parameter for the supply of mass from vegetation in tank B (mm/hr).