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On The Physical and Chemical Properties of Throughfall and Stemflow

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Abstract

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 to rainfall characteristics. Certain factors, such as the kinds and size of trees for stemflow and the distance from the stem for throughfall, were also investigated to determine their relationship to the quantity and quality of SF and ThF. To check the observed data, a tank model is used to model SF and ThF rate and concentration. Results shows 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 is highly dependent on the tree both for the rate and the quality. 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 rate and quality.

Keywords: Throughfall, Stemflow, Tank Model,Chemical Properties

Introduction

Most present day models of water flow through the soil utilizes rainfall both in quantity and quality as the direct input to the soil system. However, it is a known fact that for forested basins, vegetation once intercepts rainfall which in turn delivers it to the soil. If the effects of vegetation on the intensity, quality and time of delivery of the water that infiltrates into the soil is negligible, then we can generally neglect its presence. However, since it has been reported that vegetation interacts with rainfall quality (Roda et al. 1990, Lelong et al. 1990) and more considerably on intensity (Brown and Barker 1970, Johnson 1990, Hashino et al. 1991,1992, Sakamoto and Murota 1992), its effects obviously cannot be neglected especially in event flow quantity and quality modeling. However, until the present, there has been no definitive study on the physical and chemical effects of basin vegetation on the resulting water that infiltrates into the soil. Because of this, it would be desirable to study the properties of stemflow and through fall resulting from canopy interception of rainfall. This research determines the effects of vegetation on the physical and chemical properties of rainfall.

Study Area

The basin studied in this research are small watersheds located in Inuyama City in Aichi Prefecture. The basin areas are171,000 m^2 for basin A and 8800 m^2 for basin B. The vegetation map of the basins can be seen in figure 1. In the lower left hand side of basin A, as in most higher elevation portions of the watershed, the vegetation consists of broad leaf trees (Oak, Mountain Cherry, Camellia, Hackberry and Wisteria). On most lower elevation portions 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 on basin B where the vegetation is deciduous or broad leaf-type.

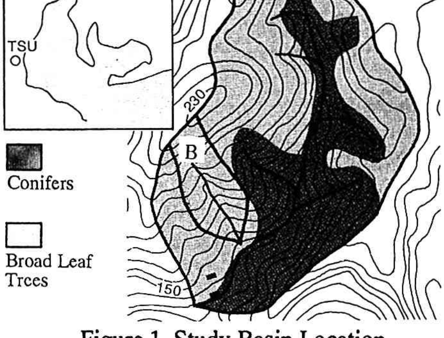

Figure 1. Study Basin Location

Physical and Chemical Properties of Stemflow and Throughfall

Information on the water budget, both in terms of water quality and quantity, of forest canopy is very important especially for modeling rainfall infiltration and tracer transport through the soil.

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Lelong et al. (1990), Roda et al. (1990) and Sakamoto and Murota (1992) has found that forest canopy changes the characteristics of the rainfall through distribution into stemflow and throughfall, which in turn changes the quality and intensity of the resulting water that is delivered to the soil. Moreover, Hashino et al. (1991, 1992) have shown that the water balance of these canopy components can be sufficiently modelled using tank models of varying complexities. What seems to be lacking is a complete discussion of the changes in rainfall rate and concentration as it falls through the trees down to the soil. In this research, it is intended to model the stemflow and throughfall components of the flow through a simple tank model whose properties are derived from observed characteristics of these components. Through this modeling, basic parameters that govern the chemical and physical processes of vegetation interception will be derived.

From the small observation basin, stemflow and throughfall intensity and water samples were collected from the period of June 1992 to October 1993 comprising of 13 rainfall events. For the stem flow, collar-like devises similar to those from Voight (1960) were attached about 1 meter from the base of the tree. These collectors divert water into automatic tipping bucket gages of different sizes depending on the tree. Five stemflow collectors were used, the characteristics of which are summarized in table 1-a. For throughfall, rectangular and circular collectors were placed at different positions and distances from trees. The throughfall summary can be seen in table 1-b. One rainfall event with stemflow and throughfall data can be seen in figure 2. Here the graphs represent, from the top, the rainfall intensity, outflow chemograph and hydrograph, rainfall chemograph, stemflow1 chemograph, and 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 smaller contact time between the rainwater and the leaves for the throughfall as compared to the stemflow. Another possible reason is difference in leaching rates of certain ions that contribute to the conductivity of throughfall and stemflow water.

To determine the relationship between stemflow, throughfall and rainfall, we plotted the cumulated rainfall versus the total stemflow and throughfall in figure 3. In this figure, *ThFB* and *ThFC* are from 1992 data while ThF_{ave} are average throughfall data for 1993 events (average of *ThF1* to *ThF4* sampling points). Also *SF1* to *SF7* represents sampling points as described in table 1. The stemflow intensity are computed using effective tree flow areas estimated from paint tests which will be described later.

Lumped Characteristics of Throughfall

Initially we investigated the characteristics of throughfall irrespective of the distance from the nearest tree, nor the kind of tree it was nearest to. This approach can be done because the observations were done on trees whose foliage more or less completely intercepts the rainfall with no considerable open areas in between trees.

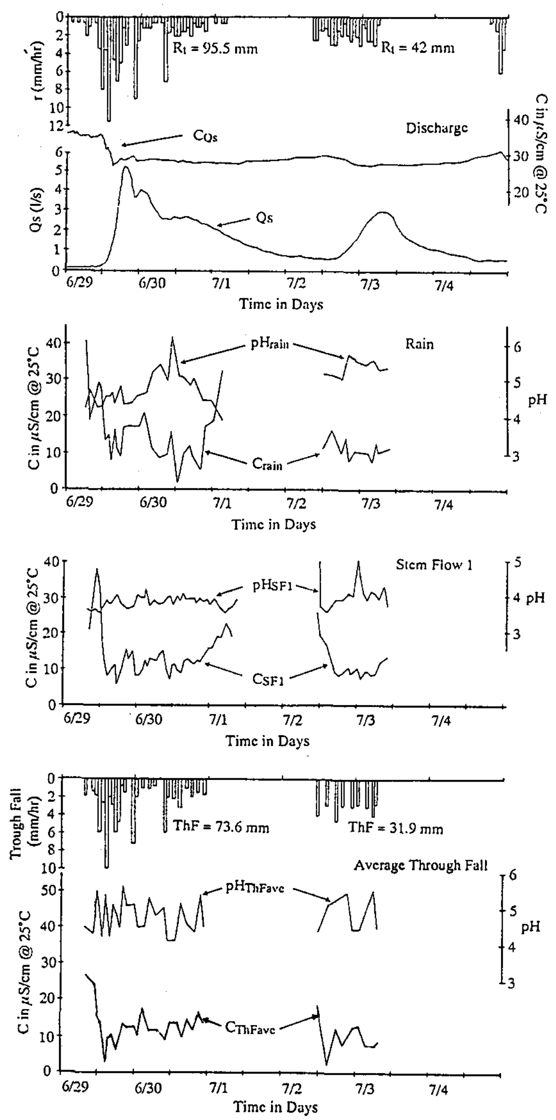


Figure 2. Discharge, Rainfall, Stemflow 1 and average Throughfall quality for the rainfall event of June 29, 1993 to July 4, 1993.

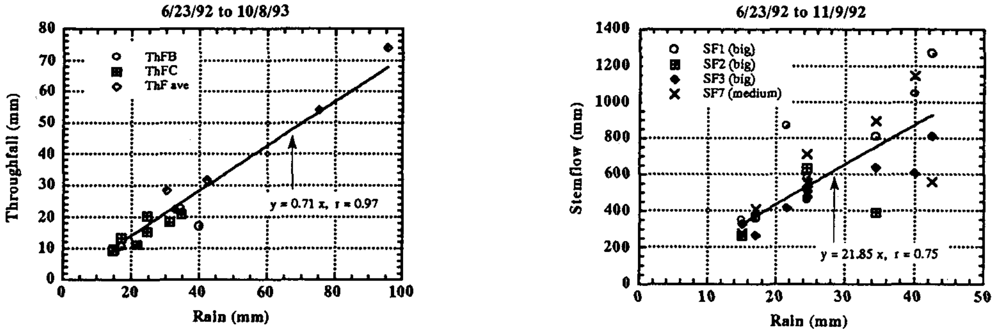
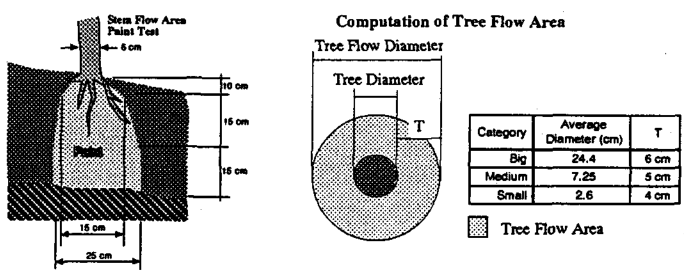


Figure 3. Lumped Throughfall and Stemflow Versus Rainfall for 13 Rainfall Events from June 1992 to October 1993.

For the throughfall plot in figure 3, a very good fitting was produced describing a ratio of 71 percent. This means that 71 percent of the total event rainfall becomes throughfall. For the conifer covered sections of 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 by 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 lack of considerable rainfall. However, Brown and Parker (1970) have shown that throughfall was not significantly different between trees of a single group or between seasons. Also, Helvey and Patric (1965) have shown that throughfall does not considerably differ for trees of different ages, although Johnson (1990) reports that this may not be the case for the same tree groups located in different basins.

Lumped Characteristics of Stem Flow

As for the stemflow, one of the most difficult assumptions to be made is the computation of the effective stemflow area so that volume measurements can be converted to intensity units. 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, namely; big, medium and small. The tree flow areas were then computed at a level ten centimeters below the surface level as can be seen in figure 4. For the big 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 observed to be 5 centimeters, and for small trees (less than 5 centimeters in diameter), the width is 4 centimeters. Using these observations, the stemflow intensities were computed as can be seen in figure 3. The fitted line shows a wide variation of data points with a regression coefficient of 0.75. This is because we assumed a constant value for the tree flow ring diameter 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 becomes sensitive to the assumed ring diameter. The observed value of 6 centimeters maybe a bit too big for the big tree category which showed the most scatter in the plot. Backsolving, it was found that to obtain a regression coefficient of 0.9 for the fitting line, a ring width of 5.8 centimeters (instead of 6 centimeters) should be used for the big tree category. However, since these are just arbitrary values, it is deemed that the assumptions are enough. The results of the fitting shows that the typical stemflow intensity is about 22 times that of rainfall.



Category	Average Diameter (cm)	T
Big	24.4	6 cm
Medium	7.25	5 cm
Small	2.6	4 cm

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

Factors That Affect Stem Flow and Throughfall Characteristics

Table 1. Summary of Stemflow and Throughfall Data.

(a)	Vegetation				SF/r				C_{SF}/C_r [pH_{SF}/pH_r], ave. of hourly ratios	
	Tree	Trunk Dia (cm)	Inclinat-ion(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
Stem Flow 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]
Stem Flow 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]
Stem Flow 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]
Stem Flow 4 (SF4)	Camellia	8.3	0	6.1	5.4349	5.9	11.63	2.57	1.323 [1.001]	1.414 [0.935]
Stem Flow 7 (SF7)	Oak	9.2	0	3.0	29.736	23.95	29.0	28.62	1.152 [0.937]	0.841 [0.842]

(b)	Vegetation			Event Trough 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
Through Fall 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]
Through Fall 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]
Through Fall 3 (ThF3)	Oak	9.0	0.8	72.7 [0.76]	33.9 [0.81]	0.919	0.983	1.236 [1.016]	1.2 [0.940]
	Oak	9.0	0.8						
	Hackberry	34.0	1.5						
Through Fall 4 (ThF4)	Camellia	9.0	1.1	84.0 [0.88]	39.9 [0.95]	1.146	1.119	0.951 [1.001]	1.169 [0.952]
	Oak	55.0	1.9						

The above discussions are for lumped systems, which means that they are values for all the sampling points irrespective of the tree kind or category for the stemflow, and the distance from the nearest tree for the throughfall. To determine the effects of these factors, we also summarized data per sampling point with pertinent data about the tree kind and category for the stemflow, and distance from the nearest tree for the thoughfall collectors. This can be seen in table 1 which also shows chemical ratios of the stemflow and throughfall with rainfall per collector. From this table, it can be seen that the stemflow rate is tree-size independent. It also shows that throughfall intensity is independent of the distance of the collector from the nearest tree. These results agree with the results by Brown and Parker (1970) and Helvey and Patric (1965) which showed that throughfall and stemflow do not differ for different-sized (or different age) trees of a single group. As for the chemical characteristics of the stemflow and throughfall, table 1 shows that canopy interactions produced throughfall and stemflow which are greater in conductivity compared to the rainfall. This can be seen in the persistently high ratios of stemflow to rainfall conductances. As for the pH, the results shows that the stemflow produces consistently more acidic flows while throughfall produces flows which are less acidic. These results agree with those observed by Roda et al. (1990) in a holm-oak forest in NE Spain.

As for the other factors that control the characteristics of the stemflow and throughfall, the kind of tree 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 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 forested with overlapping foliage thus removing the actual effects of the thinning of the canopy as the distance of the collector from the tree trunk increases. Generally however, Johnson (1990) has shown that there is a tendency of the throughfall to increase as the

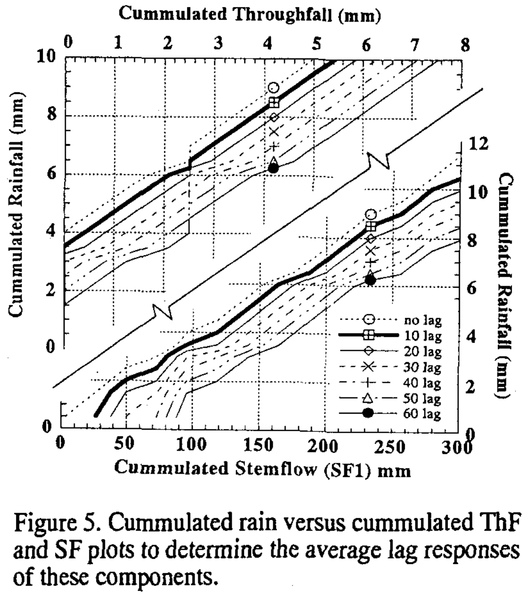


Figure 5. Cummulated rain versus cummulated ThF and SF plots to determine the average lag responses of these components.

distance of the collector from the tree stem increases.

Checking Observations Using Tank Model

Another important problem to consider is the dynamic characteristics of SF and ThF. This means the properties of these components with regards to the apparent storage capacity of the trees or the time lag of delivery of rainwater to the soil. To determine the average lag of the SF and ThF, cumulated rainfall is plotted against cumulated SF and ThF with varying lagged responses shown in figure 5. These relationships will show the average response time of both the stemflow and the throughfall. In figure 5, it can be seen that the most linear relationships are those for a 10 minute lag for ThF and also a 10 minute lag for SF. This means that the rainwater has a considerable residence time in the leaves as compared to the stem. These results are logical because of the differences in the physical shapes and orientations of the leaves that produce throughfall and the tree trunk and branches which produces stemflow.

From the above observations, a tank model is used to simulate the effects of vegetation interception on the quantity and quality of water that is delivered into the soil system. Through this kind of analysis we intend to derive basic chemical and physical parameters not obtainable by static analysis of observed data. The model comprises of just two tanks in series for all tree groups. This is because of the finding that intensity ratios does not significantly change for different tree categories. Schematically, the model can be seen in figure 6. In this model the upper tank simulates canopy interception which distributes rainwater into stemflow and throughfall, and the second tank becomes the stemflow component. The upper tank (tank A) has two orifices located at points h_A distance from the bottom. The continuity equation and the outflow for tank A thus becomes equation (1), where h is the height of water in tank A, r is the rainfall intensity and k_A is the orifice coefficient. One of the orifices of tank A becomes throughfall and the other becomes the input to the stemflow tank. The height h_A is the apparent storage of the foliage which causes a time lag for both stemflow and throughfall during initial rain. The outflow from tank A is divided into throughfall outflow and stemflow input respectively using equation (2), where α is a distribution parameter assumed so that the total r/ThF ratio would more or less be equal to the observed rainfall-throughfall ratio data (figure 3). The height of tank A is taken to be H_A. This permits overflow during intense rain periods, which becomes throughfall. The lower tank has a single orifice located at a height h_B from the bottom. For this tank the continuity equation and the stemflow rate is given by equation (3), where h' is the water height for this tank and k_B is the orifice coefficient. To account for evaporation, it is assumed that during periods of no rainfall, constant evaporation takes place which empties both tanks in a period of one day which is given by equation (4). The initial and boundary conditions are given in equation (5). Also, q_o is the outflow from tank A when the water is up to the brim.

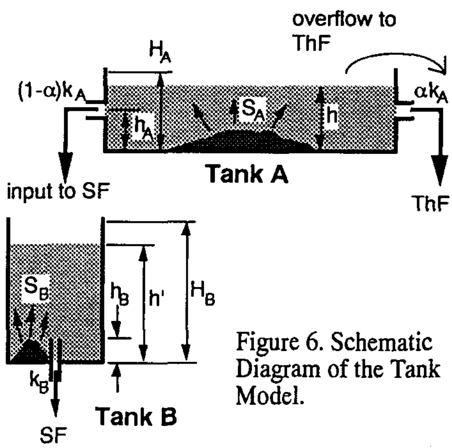


Figure 6. Schematic Diagram of the Tank Model.

$$\frac{dh}{dt} = r - k_A(h - h_A) \quad q = k_A(h - h_A) \tag{1}$$

$$ThF = \alpha q \quad SF_{input} = (1-\alpha)q \tag{2}$$

$$\frac{dh'}{dt} = (1-\alpha)q - k_B(h' - h_B) \quad SF = k_B(H - h_B) \tag{3}$$

$$\frac{dh}{dt} = -\frac{h_A}{1\text{ day}} \quad \text{and} \quad \frac{dh}{dt} = -\frac{h_B}{1\text{ day}} \tag{4}$$

$$\begin{array}{lll} & \text{at } t = 0, & h_A = h_B = 0 \\ \text{tank A} & \text{if } h > H_A, & h = H_A \\ & & q = q_o = k_A(H_A - h_A) \\ & & ThF = \alpha q_o + (r - q_o) \\ \text{tank B} & & H_B = \text{large enough} \end{array} \tag{5}$$

$$\begin{array}{l} h\dfrac{\partial C_A}{\partial t} = (C_r - C_A)r + S_A \\ h'\dfrac{\partial C_B}{\partial t} = (C_A - C_B)(1-\alpha)q + S_B \end{array} \tag{6}$$

To model concentration change in stemflow and throughfall, it is assumed that the concentration supply coming from the vegetation is constant during wet periods. The mass balance equation for tank A and B therefore becomes equation (6), where C_A and C_B are the concentrations of the storage in the tank, C_r is the rainfall concentration and S_A and S_B are the constant supply of mass from vegetation.

The results of the modeling is shown in figure 7. The plot covers the rainfall event of June 29, 1993 to July 1, 1993. The rainfall intensity and concentration for this event can be seen in figure 2. Figure 7 shows the throughfall intensity as the bar graph at the top with the computed ThF intensity as the broken line. The throughfall and stemflow concentrations are also shown, both observed (solid lines) and computed (dashed lines). The storage height for tank B was assumed to be 0.1 millimeters because no apparent lag was found in the r-SF plots in figure 5. The parameters h_A and H_A were assumed to be equal to 1 and 2 millimeters respectively, to simulate the physical properties of the leaves. The parameter α was assumed to be 0.6. To obtain a good fit for the concentrations, the concentration parameters (S_A and S_B) were found to be 7 and 0 for tanks A and B respectively. This would mean that the foliage has a greater amount of ions compared to the tree trunk (which can be explained by the big difference in exposed areas of these two components). Another possibility is that since the present assumption does not permit direct input of rainfall into the stemflow component, fresh rainwater gets in contact with the leaves first (thus big reaction towards equilibrium) and then it flows into the stem (almost in equilibrium thus minimal reaction).

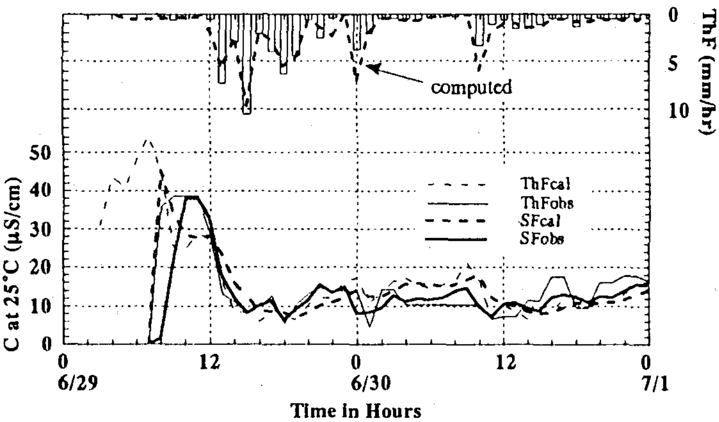


Figure 6. Computed intensity and concentration data from the proposed tank model fitted to the observed data of June 29, 1993 to July 1, 1993. Parameters: k_A=0.9 (hour^{-1}), k_B=0.9 (hour^{-1}), h_A=1.0 (mm), h_B=0.1 (mm), H_A=2.0 (mm), α=0.6 (-), S_A=7 (μS/cm mm/hr), S_B=0 (μS/cm mm/hr).

As can be seen in this figure a very good fitting of the computed data was done both for quantity and quality modeling. However since this event lacked stemflow intensity data, no fitting was made on this quantity. Using the same parameters for different rainfall events with stemflow intensity data produced good fitting curves. Presently, the problem of quantifying the parameter α is one problem. Another is the possibility that overflow from tank A may be intercepted by other branches thus contributing to stemflow. Still another is the possibility of a time-dependent or rainfall intensity-dependent function for the parameters S_A and S_B. Although a great deal of improvement can still be done on the modelling part of this research, 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 on 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 through observations of 13 rainfall events for a watershed with deciduous and coniferous vegetation. Characteristics of the resulting throughfall and stemflow were analyzed in comparison to rainfall characteristics. Other factors, such as the kinds and size of trees for stemflow and the distance from the stem for throughfall, were also investigated to determine their relationship to the quantity and quality of SF and ThF. To check the observed data, a tank model is used to model SF and ThF rate and concentration.

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 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 the tank model is found to be sufficiently capable of modeling SF and ThF rate and quality which can give us a clue to the actual physical and chemical properties of the vegetation interception process.

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