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Hysteresis Observed In SC vs. Q Relationships and Its Implications On Flowpath Identification

Werellagama, D.R.I.B.*, Matsubayashi, U.** and Takagi, F.***

The hysteresis shown in specific conductivity (SC) - discharge (Q) relationships during rain events has been previously utilized to verify the presence of preferential flows of new water. This series of observations were made in a catchment where isotopic data have shown that stored water is the predominant outflow during rainfall events. The SC response during rain events and a laboratory column test complemented the conclusion of isotopic study, viz. the runoff mechanism is discharge of stored (non-event) water. It is shown that any runoff mechanism giving a higher SC in the falling limb of hydrograph (for the same Q value) will generate an anti clockwise hysteresis in the SC-Q relation, even in the absence of a preferential flow of new water.

Keywords: Groundwater Ridge, Preferential Flow, Specific Electrical Conductivity, Flowpath

1. INTRODUCTION

In the water resources studies the analysis of solute concentration-discharge relationships during and after individual rain events is a useful indicator in verifying the response and spatial distribution of sediment sources. Many researchers, including Walling and Foster, (1975); Pilgrim et al. (1979) and Matsubayashi et al. (1993) have used the direct relation existing between the concentration of dissolved solids and the conductance in simple dilute solutions, in using Specific Electric Conductivity to represent the solute concentration. Specific Electric Conductivity, in addition to being an overall indicator of total ionic response, is preferred due to its ease of measurement and continuous data recording.

The plot of Solute concentration vs. Discharge (or Specific Conductivity vs. Discharge) relationship for an individual runoff event displays a clockwise or anti clockwise hysteresis. De Boer and Campbell (1989) cited previous literature to show that clockwise hysteresis has been associated with a decrease in the suspended sediment during the runoff event, and with an increase in the proportion of baseflow and a reduction in rainfall erosivity during the falling stage. Clockwise hysteresis has been observed when the sediment source was near the channel, and anti clockwise hysteresis has been observed when the sediment source was located in the upper part of the slopes. De Boer and Campbell (1989 and 1990) and Matsubayashi et. al (1993) have utilized sediment concentration and the specific electric conductivity (SC) variation with stream discharge (Q), to verify the presence of fast flows during rainfall events.

SC has been traditionally used to calculate the old (pre-event) and new (event) water contributions to a storm hydrograph. Many of the published data for SC measurements, e.g. Pilgrim et. al. (1979), De Boer and Campbell (1990), Muraoka and Hirata (1988), Matsubayashi et al.(1993) etc., show the SC decreasing with the rising limb of the hydrograph and then recovering to the original level during the falling limb. Some other researchers including Gillham (1984) etc. have indicated the phenomenon of rising specific conductivity during and after the discharge peak. It is impossible to apply the traditional hydrograph separation method to this type of catchments. In Kanedaira catchment too, the stream SC showed a rising behavior for dry antecedent conditions. While the SC vs. Q hysteresis reported in literature was for catchments showing SC falling type

* Student Member, Graduate Student, Department of Civil Engineering, Nagoya University, Chikusa ku, Nagoya 464-01.
** Member, Associate Professor, Department of Geotechnical & Environmental Engineering, Nagoya University.
*** Member, Professor, Department of Geotechnical & Environmental Engineering, Nagoya University.

behavior, this paper analyzes the SC vs. Q hysteresis in a SC rising case, in a catchment where preferential flow of new water is not the dominant flow mechanism.

2. EXPERIMENTAL HILLSLOPE

The Figure 1 shows the Nagoya University Experimental catchment in Kanedaira in Southern Gifu prefecture; where the current experiments were carried out. The catchment details are given in Matsubayashi et. al (1990). The top soil layer of about 1.1 m depth is underlain by weathered granite. This catchment is 7.8 ha in area and the slopes are short with a mean gradient of 30°. The elevation difference is 620-750 m. The channel mean gradient is about 14°. The vegetation in this catchment is mainly Japanese Cedar and Japanese Cypress. Mean annual rainfall in this area is 1745 mm. The observations discussed in this paper were obtained in the summers of 1995 and 1996.

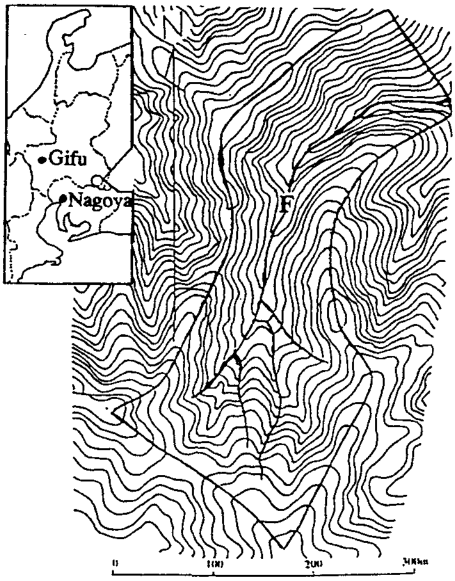

Figure 1: Kanedaira Catchment

3. RESULTS AND DISCUSSION

3.1 Physical Observations

The Specific Electric Conductivity (SC) was continuously measured for streamwater and these values were standardized to a temperature of 25°C. The temperature variation during the sampling was mild with the coefficient of variation about 2%. Stream discharge (Q) was measured and automatically recorded using a Parshall Flume at the location F shown in Fig 1. Area above the flume is 4.98 ha. Rainfall was measured using a tipping bucket rain gauge. All the data were continuously recorded by coupling to Kadec automatic data recorders (Kona Systems Co.). The interval between each data recording was 10 minutes.

The four rain events analyzed had total rainfalls of 31, 22, 35.5 and 67 mm respectively. The antecedent rainfall values given by $\sum P_i / i$ (Sklash et. al.; 1986) [where P_i is the total rainfall of the i th preceding day] were 6.2, 2.4, 106.5 and 20 mm/day respectively for the four rain events. The distribution of antecedent rainfall is shown in Figure 2. According to these data, rain events 1, 2, and 4 can be categorized as rains with dry antecedent conditions, rain event 3 having wet antecedent conditions. The width of the possible contributory areas for the 4 rain events, calculated considering direct runoff only, were 7m, 5m, 17m and 25m; per unit length of the channel respectively

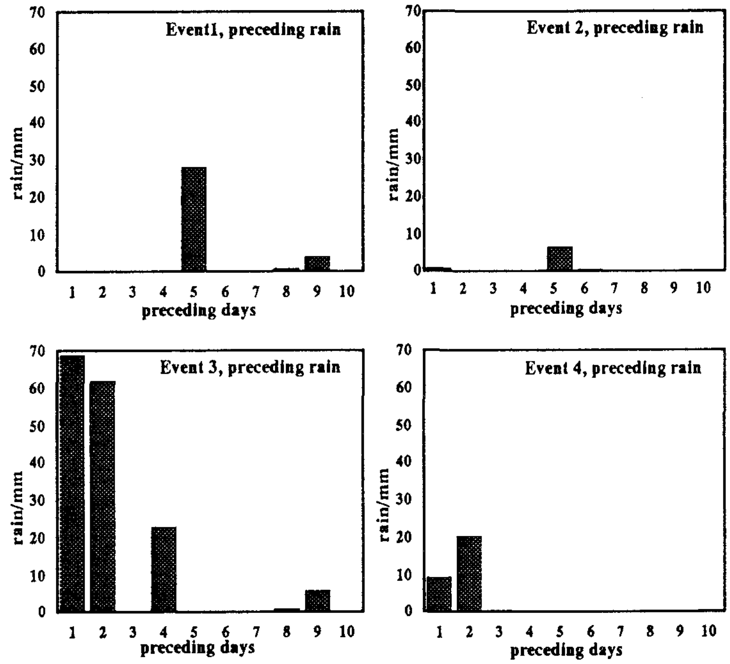

Fig 2: Distribution of Antecedent Rainfall

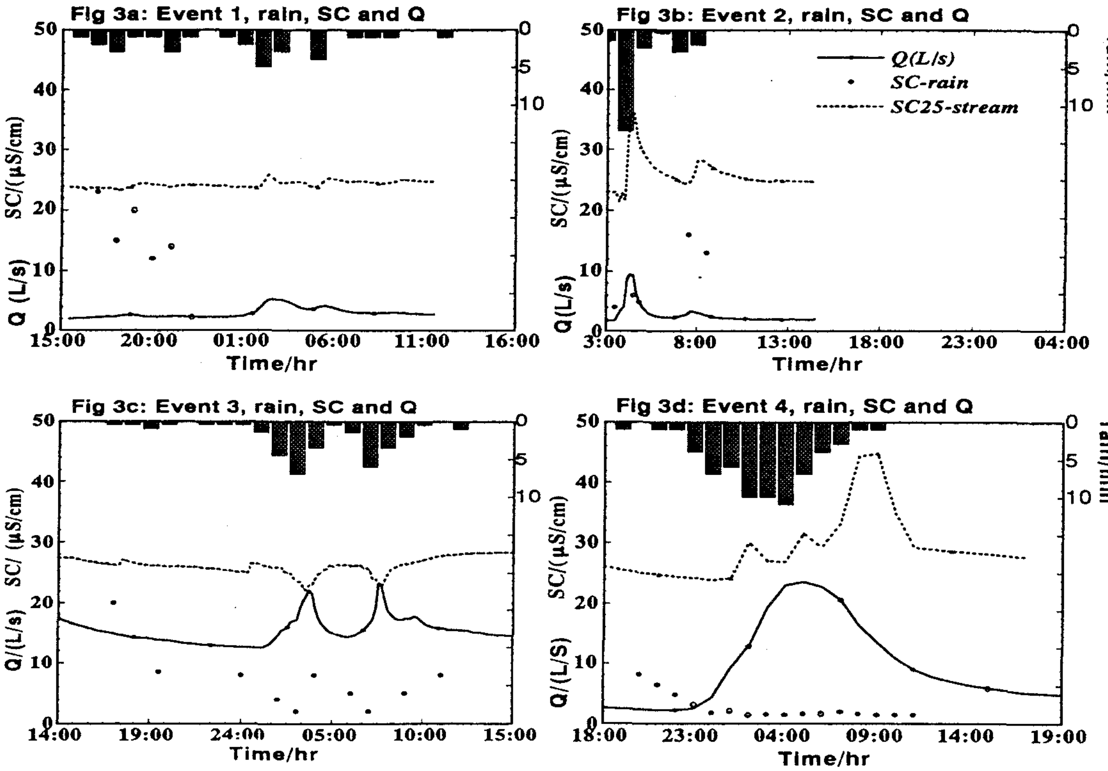

Figure 3: Temporal Variation of Discharge, SC and Rainfall

The rainfall distribution during the considered rainfall events along with temporal variation of Discharge (Q) and SC values of rainwater and streamwater are shown in Figure 3. Visual observation during rain events showed no surface runoff, indicating subsurface flow.

3.2 Flow Mechanism in the Kanedaira Catchment

The fact whether the subsurface flow seen in Kanedaira is due to the rapid throughflow of new water (i.e., preferential flow of new water) or the displacement of old water was a point addressed in previous investigations. Matsubayashi et al. (1990), discussing on hydrograph separation based on the kinematic wave method and the $\delta^{18}O$ tracer concluded that more than 80% of the direct runoff in the Kanedaira catchment occurs as the outflow of groundwater. While noting that this behavior is contradictory to the traditionally held view of a runoff model they suggested that the volume of new water in the quick flow may be accounted almost entirely by the channel precipitation and near stream saturation overland flow.

Werellagama et. al. (1997), analyzing the very rapid stream response to the rainfall in this catchment suggested a groundwater ridge (Sklash and Farvolden, 1979) type flow mechanism as the near stream flow mechanism of this catchment, with the estimated immediate contributory area within few meters of the stream bank.

3.3 Streamwater SC Response to Rainfall

While in most of the SC studies reported in literature the SC drops with hydrograph peak, in Kanedaira, SC was observed to rise with hydrograph peak. The time variation of SC (Fig. 3) shows almost immediate Q and SC response to rain input in all the rain events. Considering that events 1, 2, and 4 were events with low antecedent rainfall, while event 3 had high antecedent rainfall, it can be seen that the stream SC shows rising tendency for initially drier conditions, and decreasing tendency for initially wetter conditions. The rainfall inputs of SC were quite lower than stream SC and it could not explain the variation of stream SC with rain peak.

In this catchment, no surface runoff was found during the storms, but the stream response to the rainfall was almost immediate. Since no surface flow was evident, the contribution to the discharge peak might have come from the subsurface flow. If the subsurface flow was preferential flow of new water, the SC and isotopic data should show the contribution of new (event) water.

But considering the isotopic data observation that the stored water is the predominant outflow during rainfall (Matsubayashi et.al.; 1990), the rise of SC can be attributed to the flushing out of water which had been in storage for a longer time, and having a higher SC. The inversion of SC in the rain event 3 reflects the effect of smaller contact times between stored water and soil matrix due to the high antecedent rainfall.

Therefore considering SC and contributory area data it is shown that for events 1 and 2; the flow mechanism was near stream (groundwater ridge type response) and that for events 3 and 4, in addition to the near stream response, the upslope water also contributed laterally, fast enough to have an effect on the hydrograph, after a given time. In the case of event 3, this lateral flow seems to be the result of increased hydraulic conductivity due to very high antecedent rainfall (Werellagama et al., 1997). In the event 4, due to the high intensity of the rain peak, the flow seems to have infiltrated upto the impermeable horizon, and flowed along that, contributing to the hydrograph, especially during the recession limb.

3.4 Contact time- SC Relationship

Matsubayashi et al. (1993) describe the results of washing test of a soil core with recycling of the wash water. This gives the SC-tc (Specific Conductivity - Time of Contact) relationship. This test simulating subsurface flow, shows that the SC of the infiltrating rainwater will increase as it travels through the soil in a hillslope and will reach a steady (high) value after about 3 days with minute increases of SC in the subsequent days.

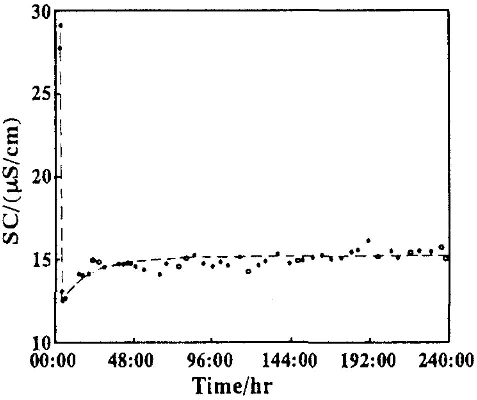

Fig. 4: SC - Contact time relationship

A similar subsurface wash test was carried out for a field soil sample obtained from Kanedaira catchment. In this case the initial solution was deionized water. As shown in Figure 4, the soil quickly exhausted it's ion supply at the water application, and took about 3 days to reach a steady value. This behavior of a field sample shows that once washed, the soil layer will take some time to reach a steady SC value, hence supporting the argument about the SC of the rain event 3 which pushed out relatively new water, with a lower contact time, hence resulting in the SC inversion seen at the discharge peak.

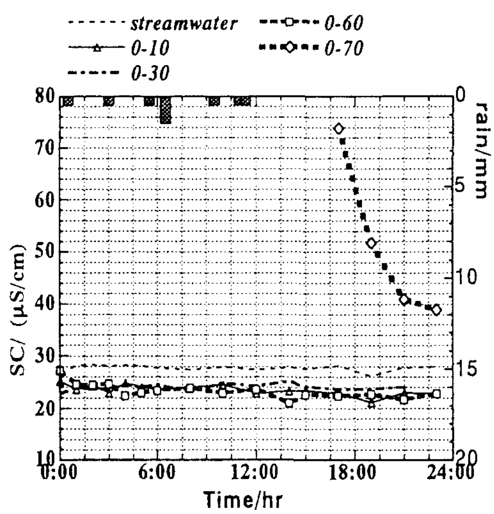

Fig 5: Event 6, Soilwater SC

Figure 5 shows the SC behavior of soil water obtained in the summer of 1996, during a rain event of low magnitude and intensity; at a station 2m upslope from the stream. The soil water samples were obtained using ceramic samplers. While the SC of the soilwater at three depths (10, 30 and 60 cm) always showed a Specific Conductivity less than that of streamwater, the 70 cm level, which was at the weathered granite horizon, did not even yield a water sample, during the rain event. But after some hours lag, when the infiltrating water finally reached the granite layer, a sample could be obtained, which gave a high SC value. But then the SC values in this layer also rapidly dropped, showing the sudden release of ions from the surface of the weathered granite layer upon contact with water, and subsequent rapid exhaustion of ions.

This behavior of the hillslope can explain the SC rising even after the hydrograph recession of rain event 4. The rain event 4 was large enough to push in the infiltrating water deeply, so that the granite layer was washed within a relatively shorter time, this wash water then proceeding to affect the hydrograph peak. Therefore these SC data also support the observation that major contribution of the hydrograph comes from the volume of old water displaced from the stored water due to the rainfall input, while for high antecedent rain and rare events with high intensity and magnitude only, the upslope contribution also becomes significant in addition to the typical near stream response.

3.5 SC vs. Q Behavior

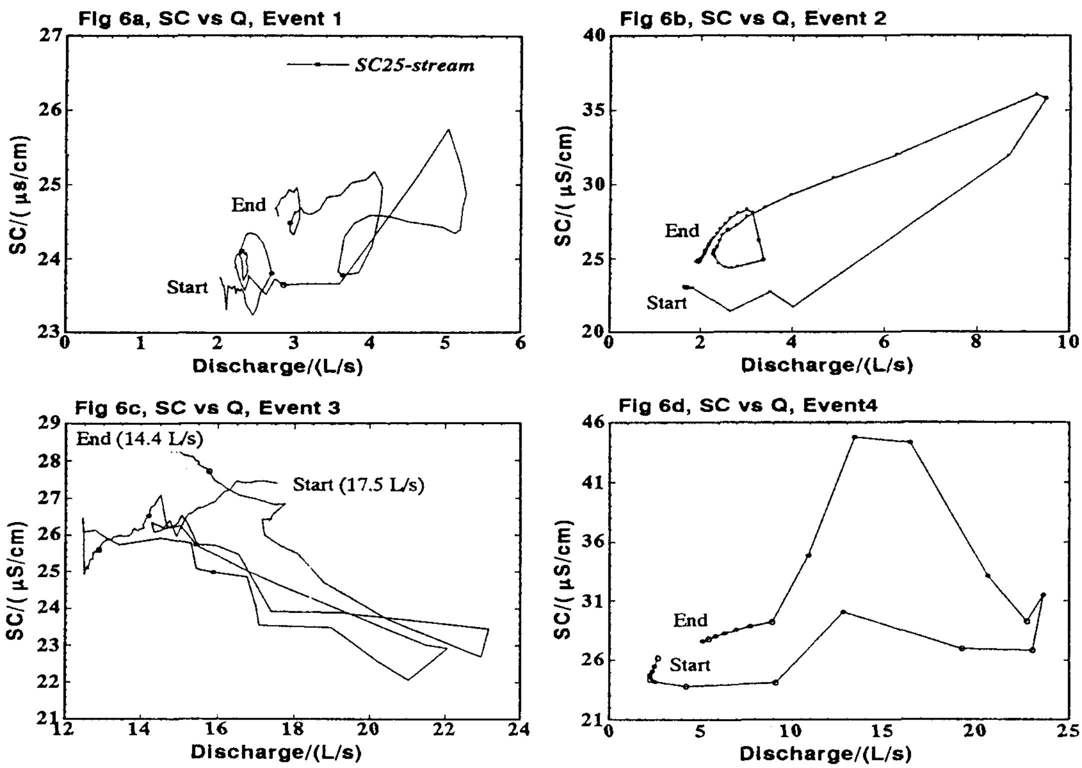

Figure 6: SC vs. Q Hysteresis

The above discussion proves that the flow mechanism of Kanedaira catchment, especially during dry antecedent conditions, is due to the pushing out of stored water, due to the new water input. In this context now we can analyze the SC vs. Q response during these rain events.

The SC and Q behavior for the rain events 1-4 are shown in the Figures 6a-6d respectively. In Figure 6a (Event 1) the SC vs. Q curve shows anti clockwise hysteresis at the rising and recession stages of the hydrograph, but at the discharge peak, we see a clockwise behavior. In Figure 6b, (Event 2) for the entire rain event the SC vs. Q curve is anti clockwise. In Figure 6c (Event 3), the curve is clockwise until the discharge hydrograph starts to rise, and then anti clockwise. At the second hydrograph peak (as shown in Fig 3c), the SC vs. Q behavior becomes clockwise for a short time only, before turning anti clockwise. For the rain event 4 , SC vs. Q shows distinct anti clockwise hysteresis during the storm. It can be seen that the curves generally show an anti clockwise trend, whether the SC is rising or falling with discharge.

De Boer and Campbell (1990) have stated that a change from clockwise to anti clockwise SC vs. Q behavior indicates the initiation of preferential flows of new (event) water. In our observations, any changes from clockwise to anti clockwise hysteresis (when shown for flood peaks of rain events 1 and 3 only), occurred only after few hours after the initiation of the rainfall, so even if a fast flow occurred, it was not a near stream phenomena. Only at the start of the Event 3, we can find behavior supportive of some kind of preferential flow of new water, but this may be due to the lateral subsurface flow as discussed in section 3.2, under time variation of SC. Also we have to consider that while SC rose for events 1,2,4 and dropped during event 3, all four SC vs. Q curves generally showed an anti clockwise trend. Further if we argue that the abrasion effect of the sediment load, should give a higher SC, as event 3 had the highest discharge, it should give rise to the higher SC due to sediment load. But the obtained result indicates the opposite. All these results complement the previous observation, viz. the source of stream SC being the discharge of stored water.

Looking at any given SC vs. Q curve either with the SC dropping or rising with the hydrograph (Q) peak, it can be seen that for a given Q value, if the SC in the falling limb is higher, it will give an anti clockwise hysteresis. If for the same Q, SC in falling limb is lower, it will give a clockwise hysteresis, regardless of the flow mechanism.

While De Boer and Campbell (1990) etc., attributed the clockwise to anti clockwise change of hysteresis as an indicator for initiation of the fast flows, it can be seen that, any runoff mechanism that gives a higher SC in the falling limb (for the same discharge) will generate an anti clockwise hysteresis in the SC vs. Q relation. Therefore even a stored water release type flow mechanism as seen in Kanedaira, will still give a similar behavior. Also both the Dinosaur Provincial park catchment in Canada described by De Boer and Campbell (1990), and Inuyama catchment in Japan of Matsubayashi et al. (1993) show SC falling type behavior during hydrograph peak. This research showed the SC vs. Q hysteresis can show anti clockwise trend irrespective of whether SC rises or falls with discharge.

4. CONCLUSIONS

The varying stream SC behavior of the Kanedaira catchment along with soilwater SC values and experimental column test results support the observation that major contribution of the hydrograph comes from the volume of old water displaced from the stored water due to the rainfall input. The SC inversion seen in the streamwater, during the event 3 was due to the displacement of stored water with a lower SC, showing the effect of antecedent rainfall.

While previous literature attribute the change of hysteresis from clockwise to anti clockwise, to indicate the initiation of the fast flows, it was shown that, any runoff mechanism that gives a higher SC in the falling limb (for same Q value) will generate an anti clockwise hysteresis in the SC vs. Q relation. This work also showed the SC vs. Q hysteresis can show anti clockwise trend irrespective of SC rising or falling with discharge peak.

Also in this type of catchment (where SC rises with discharge), the time variation of SC, rather than the SC-Q hysteresis, may give the threshold value of rainfall when the upslope inputs also have an effect on the runoff hydrographs.

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