Tracking rainfall impulses through progressively larger drainage basins in steep forested terrain

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ABSTRACT The precision of timing devices in modern
electronic data loggers makes it possible to study the
routing of water through small drainage basins having
rapid responses to hydrologic impulses. Storm hyetographs
were measured using digital. tipping bucket raingauges and
their routing was observed at headwater piezometers
located mid-slope, above a swale, and near the swale.
Downslope, flow was recorded from naturally occurring soil
pipes draining the 0.8-ha swale, Progressing downstream
from the swale, streamflow was measured at stations
gauging nested basins of 16, 52, 156, 217, and 383 ha.
Peak lag time significantly (p = 0.035) increased
downstream. Peak unitareadischarge decreased
downstream, but the relationship was not statistically
significant (p = 0.456).

INTRODUCTION

The processes involved in the delivery of rainfall from hillsides, to
swales, and through progessively larger stream channels in steep
forested watersheds are not fully understood. Most hydrologic
concepts concerning the routing of flood hydrographs have developed
from observations on large rivers. It is usually assumed that
downstream hydrographs are lagged in time and flattened to produce
later peaks and smaller unit area peak discharges (Chow, 1964). There
are few reports of hydrograph routing in small, steep upland
watersheds.
     Researchers working in steep forested watersheds generally agree
that classic Hortonian overland flow (Horton, 1933) rarely occurs
because the infiltration rate of forest soils usually exceeds
precipitation rates. Despite several studies conducted in the past
20 years, the pathways of muting rainfall into and through hillslope
soils in forested basins remain poorly understood. The presently
favored theory of subsurface drainage is that of an expanding and
contracting saturated wedge-- thatis, during the course of a storm,
the saturated zone expands up the soil profile from an area of
permanent soil saturation at the base of a slope (Hewlett & Hibbert,
1967; Dunne, 1978). When rainfall infiltrates the surface, water is
displaced downward into the saturated zone. Further upslope, the soil
is drier and the distance to saturation is greater. Therefore, one
would expect piezometric levels to rise earlier at the base of the
slope.

However, the presence of large, non-Darcian macropores dramatically changes the manner in which precipitation is routed to a stream channel. Where piping occurs, the hydraulic conductivity of the soil matrix is of secondary concern for generating stormflow (Mosley,1982; Tsukamoto et al.,1982; Ziemer & Albright, 1987). These subsurface conduits can transport water several orders of magnitude more quickly than the saturated hydraulic conductivity of the soil matrix. Saturation of the soil was thought to be necessary for water to flow through macropores and influence streamflow. However, Mosely(1982) and others have reported that large macropores permit rapid movement before the deficit in soil water storage is satisfied. These processes must be understood in order to predict the timing of water delivery from hillslopes to progressively larger streams.

THE STUDY AREA

Our study was conducted in the 483-ha drainage basin of the North Fork of Caspar Creek in northwestern California. The basin is located about 7 km from the Pacific Ocean at 30°22'N 123°43'W. The orientation of the watershed is southwest. Topographic development of the area is youthful, with uplifted marine terraces deeply incised by antecedent drainages. About 35% of the basin's slopes are less than 17° and 7% are steeper than 35°. The hillslopes are steepest near the stream channel and become more gentle near the broad rounded ridgetops. The elevation ranges from 37 to 320 m.
    The soils in the North Fork basin are well-drained clay-loams. 1 to 2 m in depth, and are derived from Franciscan graywacke sandstone and weathered, coarse-grained shale of Cretaceous age. They have high hydraulic conductivities and subsurface stormflow is rapid, producing saturated areas of only limited extent and duration (Wosika, 1981).
    The climate is typical of low-elevation watersheds on the central North American Pacific coast. Winters are mild and wet and summers are moderately warm and dry. About 90% of the average annual precipitation of 1200 mm falls during the months of October through April. Snow is rare and rainfall intensities low.
    The watershed supports a 90- to 110-year-old second-growth forest composed of coast redwood (<u>Sequoia sempervirens</u> (D.Don) Endl.), Douglas-fir (<u>Pseudotsuga menziesii</u> (Mirb.) Franco), western hemlock (<u>Tsuga heterophylla</u> (Raf.) Sarg.), and grand fir (<u>Abies grandis</u> (Dougl. ex D.Don) Lindl.). The forest contains about $700 \, m^3 ha^{-1}$ of stem wood.

OBJECTIVES

The purpose of our investigation was to verify that the commonly held assumptions concerning the routing of storm hydrographs were valid in a small, steep, forested watershed. Specifically, we investigated the lag of the start of storm runoff, its peak, and the time at which half of its volume had passed the gauging stations. This was facilitated by our ability to precisely synchronize the electronic instrumentation installed at our gauging sites. We also tested whether unit area peak discharge decreased downstream.
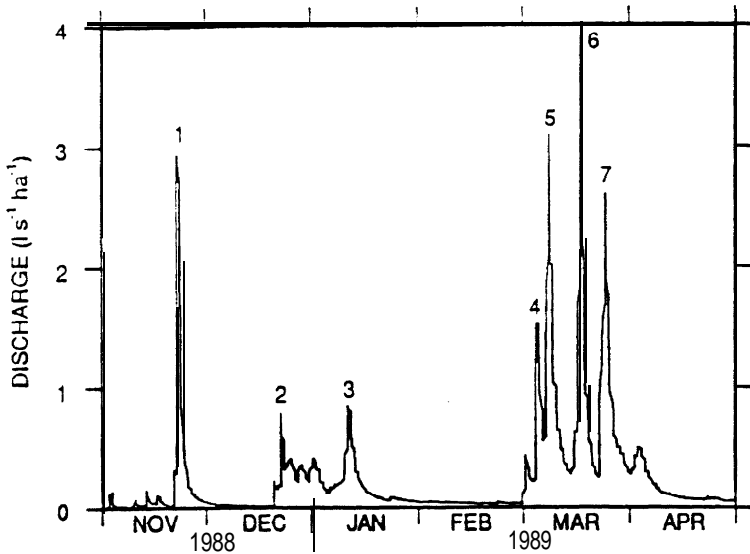
FIG. 1 Streamflow at station N during the winter of
hydrologic year 1989. The 7 storms selected for analysis
are numbered.

METHODS

Hydrologic year 1989 was a typical year at Caspar Creek.   The basin
received 1217 mm of rainfall. The seven storms that we analyzed
produced peak flows in the 483-ha basin ranging from 0.8 $l\ s^{-1}\ ha^{-1}$
to 3.5 $l\ s^{-1}\ ha^{-1}$ (Fig. 1).

Measurements

Rainfall was measured using digital tipping bucket raingauges located
at the bottom of the watershed near station N and on a ridge at the
top of the watershed (Fig. 2).   The raingauges were interrogated every
5 min.   The watershed's response to precipitation was first monitored
as a change in piezometric level measured using pressure transducers
positioned in the bottom of three piezometers.   They were located near
the upper raingauge on a hillside approximately 6,9, and 14 m upslope
from the axis of a small swale.   The transducers were interrogated
every 15 min.   Next, flow from three naturally occurring soil pipes
was measured every 10 min. The pipes drained a   0.8-ha swale and were
located about 100 m downhill from the piezometers. Downstream from
the swale, streamflow was measured at 10-min intervals at gauging
stations K, J, L, F, and A that monitor basins of 16, 52, 156, 217,
and 383 ha, respectively. Discharge at the upper two stream gauging
stations (K and J) was measured using Parshall(1953) flumes and the
next three stations (L, F, and A) were individually-rated rectangular
flumes.   The internal electronic clocks of the data loggers at all
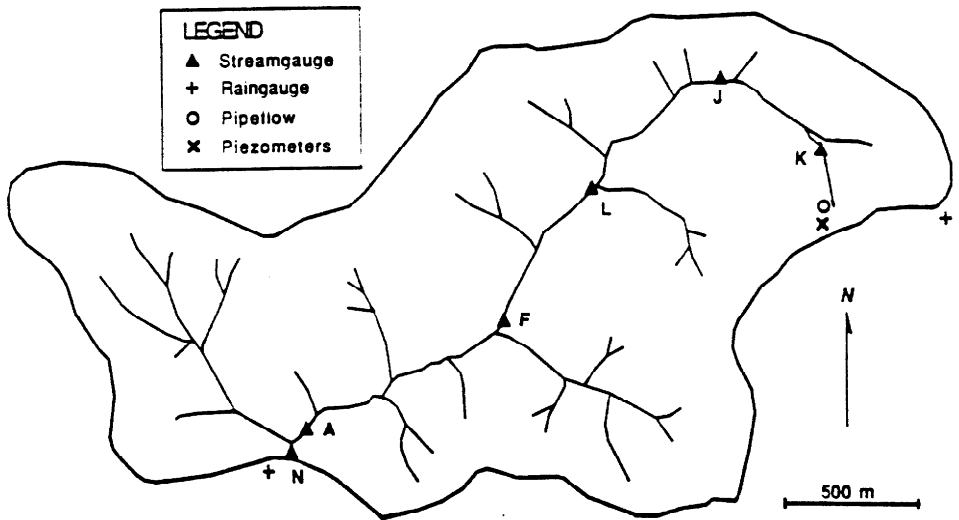stations are synchronized within a few seconds.

FIG. 2 The location of perennial streams, streamgauges,
raingauges,pipeflow station,and piezometers within the
North Fork Caspar Creek watershed.

    Station N is located a short distance downstream from station A,
but was not included in this analysis because a tributary that enters
between stations N and A (Fig. 2), representing about 20% of the
drainage area of station N,was clearcut logged in 1985 and 1986. We
anticipated that logging might affect hydrograph transit time at
station N relative to the unlogged areas, making its inclusion in our
analyses inappropriate.
    We used the mean length of the flow paths (MPF) of a station's
tributaries (Fig. 2) as a measure of its location in the drainage
network.   This seemed to be an adequate surrogate for the time of
concentration for the watershed above each streamgauge.   For example,
the value of MFP at streamgauge K is merely the length of the channel
originating below the piping site (Fig. 2); MPF at station J is the
average of the length of the K channel extended to J, the length of
the channel originating northeast of K to J, and the length of the
small channel joining the main channel just above J. MPF was highly
correlated with the square root of the drainage area(r^2 = 0.94), a
variable commonly used to estimate the size of flood peaks in a region
(Jarvis, 1942: Izzard, 1954).

●Antecedant precipitation

An antecedent precipitation index (API) "hyetograph" was constructed
from each precipitation record.   API at any time (i) was calculated
as:

$$API_i = API_{i-1} c^t + P_i \tag{1}$$

where c is the decay constant characteristic of the particular
recession, t is the time interval, and P_i is the precipitation that

occurred during the ith interval of duration t.   Using regression
analysis, we determined that the best predictor of Caspar Creek peak
discharge was a decay constant (c) equal to 0.9966 when 5-min
precipitation intervals (t) were used.   This is equivalent to a daily
decay constant of 0.375.
    The timing of rainfall at the lower end of the watershed was not
very different from that at the top of the watershed.   API peaked at
the raingauge near station N an average of 7 min earlier than at the
raingauge at the upper watershed near the piezometer site.   This
difference ranged from 0 to 20 min. The differences in rainfall
timing were always more than an order of magnitude smaller than any
computed streamflow lag times. Furthermore, these differences
approximate the 5-min sampling interval of the raingauges. It is
unlikely that there are any effects on streamflow timing due to such
small differences in precipitation timing at the two raingauges.   For
convenience, therefore. lag times were computed from the headwaters
raingauge only. The lag time was the difference   between the time of
peak API calculated at the headwaters raingauge and the time of the
feature of interest on the hydrograph from each station.

RESULTS AND CONCLUSIONS

    The dependent variables we tested were: the time of the start of
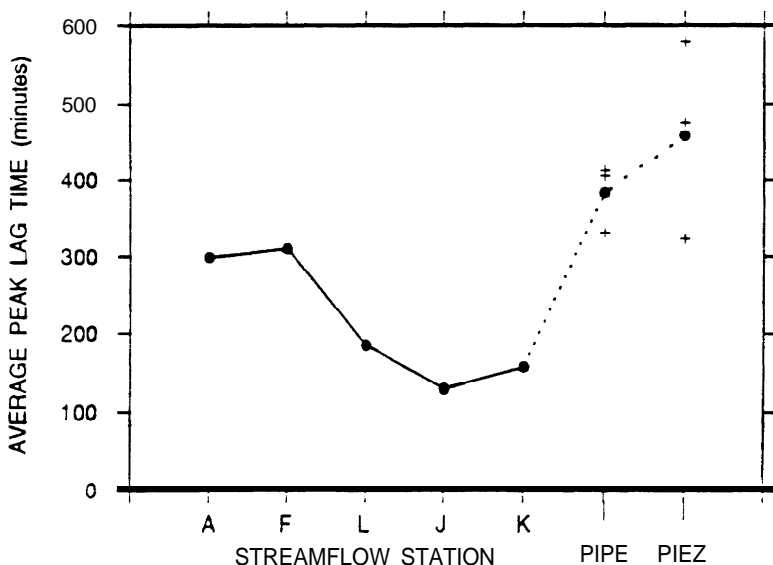rise of the storm hydrograph (SR), the time of the peak (Tp), the time

FIG. 3   The average difference between the time of peak
antecedant precipitation and the time of peak streamflow,
pipeflow, and piezometric level at each station from the
bottom of the watershed (A) to the top (PIEZ). The (+)
symbols mark the average lag times of individual soil
pipes and piezometers. The line connects the average of
the seven storms at each site.

when half of the volume of runoff had passed each gauging station
(0.5Q),and the magnitude of the peak unit   area discharge (Qp).
Regression analysis was used to test the relationship between these
variables and the mean length of the longest flow paths (MFP).

o   Our data show that for streamflow routing, there is a generally
     increasing lag in the time of the peak downstream (Fig. 3).
     However,streamflow peaks at even the farthest downstream station
     (A) arrived earlier than pipeflow peaks in a headwater swale, and
     the peaking of piezometric level on hillsides is delayed further.
        Pipeflow is delivered by capturing the groundwater macropore
     flow and matrix flow. In addition,the roughness and sinuosity of
     the pipeflow channel is probably much greater than that of open
     channel streamflow. Consequently,the timing of peak pipeflow is
     retarded relative to that of streamflow.
        Lag times of peak piezometric levels were more delayed than
     that for pipeflow. A piezometer near the swale peaked   94 min
     later than the peak of pipeflow measured about 100 m downslope.
     A piezometer higher up the slope was delayed 197 min. A shallower
     piezometer even higher up the slope peaked 61 min earlier than the
     pipeflow. The rise of piezometric levels is a function of matrix
     infiltration rate, the soil depth, and the flow rate downslope.
     Much more time is required for water to move through the soil
     matrix to a restricting layer than is required for the turbulent,
     non-Darcian movement of water in subsurface soil pipes. Much more
     work needs to be done on the flow nets of subsurface water before
     we can make conclusions about the linkages between piezometric
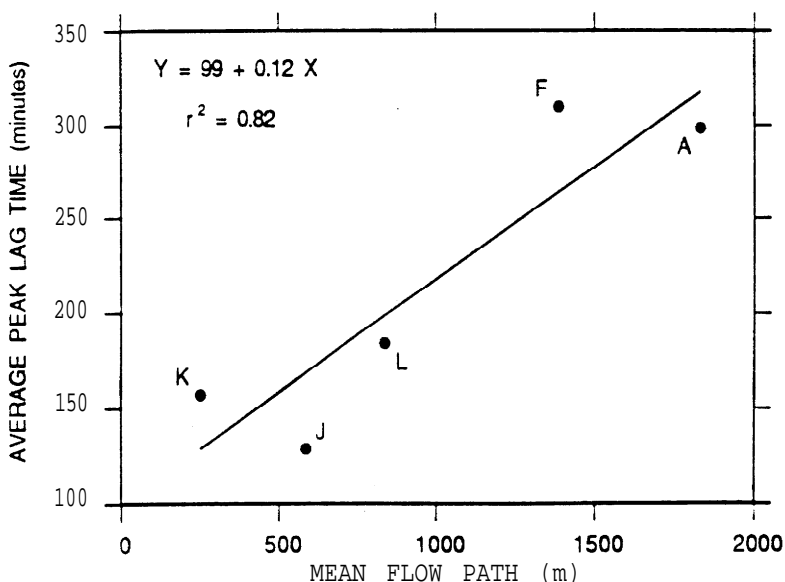   levels, pipeflow, and channel flow.

FIG. 4 Relationship between average lag time and mean
flow path at the 6 streamgauges on the mainstem of North
Fork Caspar Creek. Lag time is the difference between the
time of peak antecedant precipitation and the time of peak
streamflow.

o   There is a significant positive relationship (p = 0.035) between
    average peak lag time (Tp) in the mainstem (stations K, J, L, F,
    and A) and MFP (Fig. 4). A smaller watershed with MFP = 250 m
    (such as station K) an average peaked about 155 min earlier than a
    larger watershed with MFP = 1800 m (such as station A). This
    follows conventional wisdom that it takes longer to route a peak
    through larger watersheds.

o   There was a negative, but statistically insignificant (p = 0.575),
    relationship between the lag time of 0.5Q and MFP. This implies
    that the shape of the hydrograph was not shifted by drainage path
    length. Sendek (1985) reported that lagging the South Fork did
    not influence 0.5Q lag time.

o   There was no relationship (p = 0.998) between the lag time of
    start of rise (SR) and MFP. When the smallest storm is excluded,
    the relationship improved (p = 0.457), but was still
    insignificant.

o   There was a negative, but statistically insignificant (p = 0.456).
    relationship between unit area peak discharge at the stream
    gauging stations and MFP (or square root of drainage area). Even
    if the relationship were significant, the decrease in unit area
    discharge would be much less than that predicted either by Jarvis
    (1942) or Izzard (1954).

    Considering the above findings, it appears that the North Fork of
Caspar Creek is behaving like a "small" watershed according to Chow's
(1958) classification. That is, it is responding mainly to watershed
conditions and fails to show channel storage effects.
    The precision timing capabilities of modem data loggers provide a
resolution that is a tiny fraction of the travel time of flow between
even very closely spaced gauging stations. This capability allows
various assumptions about the hydrologic responses of small steep
basins to be tested. Our preliminary findings suggest that
hydrologists concerned about small mountainous drainage basins should
avail themselves of the capabilities of modern electronic
instrumentation to determine how their basins are actually performing.

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