STORM HYDROGRAPH COMPARISONS OF SUBSURFACE PIPE AND STREAM CHANNEL DISCHARGE IN A SMALL, FORESTED WATERSHED IN NORTHERN CALIFORNIA

by

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ABSTRACT

The term piping has been used to describe subsurface erosion processes and concentrated subsurface water discharge. Physical features created by piping have been termed pipes. Piping can occur in natural landscapes due to individual or combined effects of mechanical (e.g., corrasion), chemical (e.g., soil dispersion), or biotic (e.g., animal burrowing) forces normally occurring in subsurface environments.

Piping has been observed for many climatic and geologic regimes, and under various vegetative and land use conditions. Piping has been measured or reasoned to be important to geomorphic processes and hyrologic response in various site-specific circumstances, though the general applicability of these results has not been determined.

Pipe discharge, stream discharge, and rainfall were measured for three winter storm seasons in a small forested watershed in north-coastal California. Comparisons of pipe discharge and stream discharge for 22 storm events indicated that pipes respond dynamically to rainfall inputs. This was particularly noted for storm conditions that included high-intensity rainfall and wetter soil conditions at time of rainfall. Pipe discharge peaks occurred later, and were more subdued on a unit-area basis, than peaks observed at the stream channel. Pipe runoff measured at three study swales averaged 50 to 68 percent in comparison to runoff measured at a surface channel. Pipes appeared to be a substantial source of runoff from study swales.

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INTRODUCTION

Terminology

Subsurface erosion has been described through numerous terms and definitions. Higgins (1984) classified subsurface erosion into two general categories; "erosion by shallow throughflow or outflow of soil water (piping) and erosion by outflow of groundwater (sapping)." The term "piping" has been used to broadly reference subsurface erosion involving "the formation of natural pipes in soil or other unconsolidated deposits by eluviation or other processes of differential erosion" (Chorley 1978). Eluviation is the transport of small particles in suspension through the soil matrix (Hausenbuiller 1978).

"Tunneling" is a term that has been applied to erosion initiated by water that infiltrates surface cracks and then erodes along a hydraulic gradient, though it has been used to reference other kinds of subsurface erosion as well (Crouch et al. 1986). The term "boiling", first applied by engineers to describe a cause of dam failure (Terzaghi and Peck 1948), has also been used in natural landscapes to describe conditions where hydraulic pressure promotes eluviation within the phreatic zone or soil heave in near-surface zones (Crouch et al. 1986). Subsurface erosion in non-calcareous materials resulting in surface features similar to karst topography has been termed "pseudokarst" (Parker 1964). The term "suffosion", initially introduced to describe mechanical removal of loose particles, has been used by some authors to refer to erosion caused by physio-chemical interactions within the subsurface environment (Jones 1981).

Features formed by subsurface erosion processes are variously named as well. In addition to pipe and tunnel, the term "macropore" is commonly used. A macropore is "any large pore, cavity, passage way, channel, tunnel or void in the soil, through which water usually drains by gravity" (Aubertin 1971). Beven and Germann (1982) suggested the used of the terms "preferential pathway" and "macrochannel" in an effort to emphasize the importance of soil structure on subsurface flow hydraulics. Other names used in reference to pipe-like features are "biotic holes" and "structural openings" (Whipkey 1969), "noncapillary pore spaces" and "large voids" (Hursh and Hoover 1941), "natural hydraulic pathways" (Hursh 1944), and "biological and structural channels" (Arnett 1974).

Jones (1981) has provided the most comprehensive review of literature on subsurface erosion in natural landscapes. Consistent with literature reviewed by Jones, "piping" pertains to concentrated subsurface erosion and water transport that is characterized by flow hydraulics more indicative of channelized surface or pressurized conduit discharge than of laminar transport in homogeneous subsurface matrix. "Pipe" pertains to erosion pathways that extend for some distance within the shallow subsurface environment as either continuous features or as a system of inter-connected features that form extensive, branched networks. These features or networks may connect to the surface environment at one or more locations, but are entirely contained within the subsurface environment for most of their length.

In this study, the terms piping and pipe are predominantly used. Unless otherwise indicated, their use should be interpreted according to the definitions that have been presented for these two terms.

Geographic Distribution

Recognition of the possibility of concentrated subsurface flow or erosion through pipe-like features dates at least to the 1880's, when Schumacher (1864, cited through Baver 1938) introduced the concept of capillary versus noncapillary porosity and indicated that water would move more rapidly through the latter. Von Richthofen (1886, cited through Jones 1981) briefly speculated on the hydrologic and geomorphic role of large soil pores in a loess landscape, and Cussen (1888, cited through Jones 1981) referred to caverns and underground streams formed by erosive action of water infiltrating alluvial depressions in New Zealand. Piping has since been identified or studied in highly varied settings, including arid to humid regions with greatly different geologic and vegetative conditions. Piping has been identified in Europe, Africa, China, the Southeast Pacific region, the British Isles and North America (Hansen 1989, Jones 1981, Baillie 1975). Piping has been documented in loessal, alluvial, and glacial-drift derived soils, as well as others having sharp textural changes between the A and B horizons or very clayey conditions throughout (Crouch et al. 1986, Baillie 1975).

Research Chronology

Piping has been most thoroughly documented and studied in dryland regions. Even so, comprehensive analysis and classification of dryland piping according to physical and chemical characteristics now considered important did not occur until the late 1940's and early 1950's when the USDA Soil Conservation Service sponsored piping research in the southwestern United States (Jones 1981).

The earliest and most complete serious study of pipe hydrology is associated with upland catchments in the United Kingdom, and includes work done in the 1970's as referenced by Jones (1981, 1987), Jones and Crane (1984), Wilson and Smart (1984), and McCaig (1983).

Supporting the premise that general awareness of piping in natural landscapes has only recently been recognized, Parker (1964) stated that piping was not mentioned in any of a number of technical textbooks reviewed at that time, and Jones (1981) indicated that interdisciplinary communication about piping and the establishment of a body of literature did not begin until the 1960's. Jones also stated that the earliest English textbooks to include piping processes in geomorphic and hydrologic models may have been Carson and Kirkby's Hillslope Form and Process, published in 1972, and Gregory and Walling's Drainage Basin Form and Process, published in 1973.

Causes

Fletcher et al. (1954) provided a list of five factors they reasoned to be necessary for piping to occur:

1. there must be a source of water;
2. the surface infiltration rate must exceed the permeability rate of some subsurface layer;
3. there must be an erodible layer immediately above the retarding layer;
4. the water above the retarding layer must be under a hydraulic gradient;
5. there must be an outlet for the lateral flow.

Some or all of these factors are usually mentioned by other researchers (Goldsmith and Smith 1985, Baillie et al. 1986). These factors are briefly described in the following paragraphs to illustrate their role in pipe development.

(1) Storm-event precipitation that rapidly enters and moves through the subsurface environment typically serves as the water source. Jones (1981) reports that high intensity rainfall events are frequently associated with conditions where piping occurs, though ground water can also serve as a water source through sapping.

(2) Reduced permeability can result from an impermeable base layer, or any other material discontinuity that promotes concentrated lateral flow through the overlying layer. Sloan and Moore (1984) and Freeze (1972) indicate that large hydraulic conductivity with impermeability at some depth, or any permeability reduction at very shallow depths is a common occurrence in subsurface environments. In general, change in permeability with depth can be due to textural or structural characteristics associated with soil horizons (Hausenbuiller 1978).

(3) Erodibility of the overlying layer is usually referenced in terms of dispersibility, which is primarily associated with high concentrations of expandable clay, especially montmorillonite (Parker 1964), or high exchangeable sodium concentrations in the overlying layer (Heede 1971). Dispersion is effective when three conditions are met: porosity is substantial, inter-particular bonds are weakened, and an adequate displacement force is applied (Jones 1987).

(4) Hydraulic gradient causes water movement through the subsurface environment. A large hydraulic gradient can promote eluviation where fine sediments lay within or adjacent to zones of predominantly coarser material, or corrasion where pipes have already been initiated and turbulent energy causes material to be abraded from pipe walls. Parker (1964) points out that the hydraulic gradient adequate to cause erosion in one type of material layer may not be adequate in another type.

(5) Pipe flow outlets are important to maintain steep hydraulic gradients and for ultimate removal of material from the subsurface environment (Baillie et al. 1986).

Other factors have been cited as important to pipe development and are described in the following comments. These additional factors can have a significant role in formation or subsequent development of pipes, but are generally listed as important only to the extent that they influence the five factors just described.

Susceptibility for cracking is often considered to be important (Parker 1964). Cracking is most pronounced in high-clay content materials where conditions of seasonally dry climate and poor ground cover also occur, serving to periodically dessiccate the shallow subsurface environment and weaken soil structure (Brown 1962). Cracking can also be important in humid regions due to mass movement activity (Jones 1979). The importance of dessiccation or mass movement cracking to pipe formation is most pronounced in upper soil horizons (Crouch et al. 1986). Though it is not specifically presented as a soil cracking phenomenon, Aubertin (1971) mentions freeze-thaw as a process that opens up soil layers, and also increases water delivery along concentrated pathways.

Biotic factors are frequently cited as important in initiating pipes and increasing the connectivity between existing pipes (Jones 1981). Biotic factors are most strongly associated with the vadose zone, where biotic activity is greatest (Seven and Germann 1982). Animal burrowing and root decay have been considered to be important causes of pipe formation since some of the earliest field studies of piping in humid regions (Hursh and Hoover 1941, Gaiser 1952). More recently, Whipkey (1969), Arnett (1974), Beasley (1976) and especially Aubertin (1971) have also emphasized the role of biotic activity in their field settings. Biotic activity cited by these authors include decayed root channels and tunneling or burrowing by insects, worms and animals.

Aubertin (1971) particularly emphasized the role of rooting activity in forming or connecting pipes and discussed the importance of the particular tree species involved. Different species have varying lateral and vertical root system patterns and different decay rates, resulting in differing influences on pipe development. Aubertin (1971), Whipkey (1969), and Gaiser (1952) each suggested that decayed taproots and stumps or animal activity can cause surface depressions or otherwise result in localized high-permeability zones for surface water to concentrate in--or more rapidly infiltrate through--thereby promoting pipe development.

Jones (1971) acknowledges the association between biotic factors and pipe development, but considers that biotic factors are of secondary importance compared to physical factors such as those previously listed. At a later date, Jones (1981) stated that a more current literature review supported the same conclusion.

Land management activities may also influence pipe development. Removal of vegetative cover has been considered to promote piping and subsequent gully formation since it contributes to breakdown of surface-layer soil structure, resulting in dessication cracking through drying of surface layers during warm periods and increased surface runoff during wet periods (Parker 1964). Overgrazing is the most frequently cited activity in terms of vegetative reduction leading to pipe development (Brown 1962). These land management effects are primarily cited in relation to dryland regions.

Alternatively, land management in humid regions has been considered to inhibit pipe development. Cultivation or other intensive land use can disturb continuity of pipe networks established prior to the land use activity (Nelson and Baver 1940). Burch et al. (1987) surmised that conversion from. forest to grassland resulted in reduction of macropores at a study site in Australia. In addition to reducing the connectivity or number of pipes, land management activities that disturb the soil surface can also result in blocked pipe inlets (Mosley 1982).

Geomorphic Significance

Piping is known to be important in dryland regions, where it has been documented as an important contributor to gully formation and evolution of badlands geomorphology (Parker 1964, Heede 1971). Although piping has not been adequately studied to allow any conclusions about its geomorphic significance in humid regions, Baillie et al. (1986) contend that piping research has already provided a body of knowledge that suggests piping-related erosion is active in humid regions. In one of the few studies to directly quantify sediment discharge through pipes, Jones (1987) measured sediment exiting pipe outlets at a study site in Wales. He concluded that sediment yields from high discharge pipes was well-correlated to estimations made for pipe length and contributing drainage area, and that sediment discharged from pipes to the stream course accounted for as much as 15 percent of the stream's annual sediment load.

In some cases, pipes may develop to a quasi-stable condition that persists for many years (Jones 1971). For example, Beven and Germann (1982) reported on pipe networks that appear to be 50 to 100 years old, associated with root decay in high-clay soils. They also cite research to indicate that pipe networks regulated by biotic activity can be maintained in a stable condition for many years. The long term implication of piping suggested by most research, however, is enlargement and ultimate collapse of pipe features (Jones 1981). In addition to gullying, piping effects include ground subsidence (Rubey 1967) and extension or initiation of surface channels (Jones

1971). In some cases, collapsed pipe networks have demonstrated a dendritic pattern similar to surface channel networks (Jones 1987).

A relationship between piping and mass-failure events in soils or unconsolidated sediments may also exist: Failures could be triggered by increased hydraulic pressures associated with pipes that are discontinuous (Sidle 1986) or blocked (Tsukamoto et al. 1982). This seems reasonable, based on research suggesting that pipes often initiate as discontinuous, individual features which gradually inter-connect due to seepage pressures (Mosley 1982), and it is logical to assume that a continuous pipe can become blocked as material sloughs from the pipe roof and walls.

Hydrologic Significance

Pipe hydrology has not been studied extensively, but most of the work that has been done is in humid regions (Jones 1981). Early laboratory studies that examined piping-like processes and inferred their importance to soil conditions in humid regions include Baver's (1938) research that related high permeability with non-capillary pores and Nelson and Baver's (1940) consideration of the importance of size, volume, shape and continuity of non-capillary pores in promoting rapid infiltration. Hursh (1944) considered individual biological channels as potentially important as other characteristics of the soil matrix to water drainage in upper soil-horizons.

One of the first field studies to consider the hydrologic role of piping in a humid region setting was conducted by Hursh and Hoover (1941). They examined surface runoff and subsurface flow through trench faces for a undisturbed and disturbed surface layer under forested conditions and for a formerly forested area that had been converted to cultivated crops at a study site in the southern Appalachians. Pipe discharge was not directly observed, but the authors reasoned that reduced subsurface flow observed in the latter two cases was due to reduced permeability, which in turn was due to fewer continuous noncapillary pore spaces. They surmised that discharge through biological channels and continuous macropores related to soil structure was of "first importance" to the hydrologic characteristics of the soil and suggested that discharge through these features contributed to streamflow since this water was only "temporarily detained" as it moved vertically and laterally through the soil profile.

Another early field study was conducted by Gaiser (1952), who excavated trenches in a forested soil in southeastern Ohio to document an extensive and highly inter-connected network of decayed root channels. Gaiser conjectured that these channels might serve an important function in vertical and lateral movement of free water through the soil environment, though he did not collect any hydrologic data to support this idea.

Increased interest in pipe hydrology in humid regions during the last two decades has largely focused on the possible importance of pipes in generating storm runoff. Prior to considering the importance of pipe discharge in this regard, a discussion of conventional hypotheses of runoff generation in humid regions would be useful.

For many years prior to the 1960's, storm runoff through surface channels was assumed to be governed by production of Horton overland flow according to the soil infiltration-limiting concept outlined by Horton (1933). However, field study subsequent to general acceptance of Horton's concept indicated that, for most natural landscapes of humid regions, infiltration capacities were only rarely limiting--with the greatest share of runoff during storm events seemingly generated by only small portions of watersheds rather than from basin-wide overland flow. The variable source concept, introduced during the 1960's, incorporated this idea and promoted the role of the subsurface environment in storm runoff generation (Hewlett and Hibbert 1967, Harr 1977, Dunne 1978).

Consistent with ideas outlined by the variable source concept, the mechanisms now considered important for storm runoff generation in well-vegetated humid landscapes are saturation overland flow (direct precipitation and return flow in saturated zones near surface channels) and subsurface flow (saturated and partly-saturated subsurface flow that directly inputs to surface channels) (Pearce and McKerchar 1979). According to Dunne (1983), saturation overland flow is typically more important under conditions that include less steep terrain, thin soils, and low to high subsurface permeability; subsurface flow is typically more important under conditions that include steeper terrain with convergent topography and very permeable soils that have permeability restrictions at some depth.

In most humid region forests with a deep litter layer and stratified soil conditions, many researchers consider the major portion of storm runoff to be derived from subsurface pathways (JeJe et al. 1986, Tanaka 1982, Bernier 1985). Beven (1981) reviewed field and theoretical studies to conclude that subsurface flow dominates storm runoff where conditions include steep hydraulic gradient and soils with high permeability. The volume and timing of the subsurface contribution depends on depth to impermeable base horizons, hydraulic conditions in the unsaturated zone at the beginning of storm events, and rainfall rate and duration during storm events (Beven 1981, Whipkey 1969). Dunne et al. (1975) also have stressed the importance of antecedent soil moisture status as a control on volume and timing of storm runoff.

Other researchers consider saturation overland flow to generally be the dominant mechanism of storm runoff in humid regions (Freeze 1972, Dunne 1983). Freeze stated that he doubted subsurface pathways could provide the quantity of water observed as storm runoff in surface channels. Dunne indicates that even where subsurface flow dominates storm runoff volume, saturation overland flow may determine the magnitude of runoff peaks.

Some of the first work to consider the importance of piping to subsurface water transport subsequent to the development of the variable source concept was done by Whipkey (1967, 1969) and Aubertin (1971). Both of these authors studied piping in the Allegheny-Cumberland Plateau region in the east-central United States. Whipkey and Aubertin both concluded that piping raised the overall hydraulic conductivity of soils, and that macropores rapidly intercepted and routed subsurface water. Neither author attempted to directly quantify pipe discharge contribution to storm runoff response of surface channels downslope.

The hydrologic significance of pipe discharge to storm runoff generation in any natural landscape depends on the importance of different flowpaths in generating runoff, as well as spatial and morphological characteristics of the existing pipe network (Jones 1981). In recognition of differences in spatial characteristics and hydrologic function of pipes and pipe networks, Jones (1979) classified pipes into two major categories: "disjunct", where pipes discharge onto hollows or side slopes; and those "linked to the channel net", where pipes discharge directly into, or in close proximity to, active stream channels. Considering differences in morphology and connectivity of pipes, which strongly influence pipe hydrologic function, Jones and Crane (1984) noted two groups of pipes, those that demonstrated a flashy response and those that respond in a more subdued manner during storm events. Jones (1979) observed another characteristic of pipe discharge that is presumed to be strongly related to spatial characteristics of pipe networks: some pipes at a given site may discharge perennially, others seasonally, and yet others ephemerally.

Jones (1979) and Wilson and Smart (1984) contend that pipes can serve an important hydrologic function regardless of which of the two major runoff generation mechanisms predominates in a particular natural landscape. In cases where subsurface stormflow is more important, they suggest that pipes or pipe networks that are effective at intercepting subsurface flow and rapidly transporting it to zones adjacent to surface channels can significantly contribute to runoff peaks.

Where saturation overland flow is important, Jones (1979) and Wilson and Smart (1984) expect piping to play an important role if pipes are discontinuous or constrict near their outlets, creating reservoirs of subsurface water under a pressure head and thereby resulting in quicker saturation of lower slope profiles than would otherwise be expected. They reason that piping can also contribute to saturation overland flow where pipes discharge to the surface at some distance from surface channels, hastening saturation of lower slope profiles or transmitting appreciable amounts of saturated overland flow across already saturated areas to stream channels.

A few researchers have attempted to quantify the portion of storm runoff that is attributable to pipe discharge. Jones and Crane (1984) conducted one of the first direct monitoring programs of pipe discharge. They concluded that pipes discharging in streamside zones (i.e., those linked to the channel net) provided approximately 46 percent of all streamflow in peatland soils at their study site in the United Kingdom. Wilson and Smart (1984) considered general characteristics of surface channel and subsurface water discharge--at a location near Jones and Cranes' (1984) study area, but with glacially-derived soils--for a case where pipes were known to be hydrologically active. They qualitatively estimated that about 50 percent of all storm runoff in their study area was derived from pipes, and theorized that pipes were capable of delivering five times the volume of water that was transported as either surface runoff or saturated throughflow. McCaig (1983) used conductivity measurements for pipe and near-channel saturated zones to estimate that flow from "piped areas" contributed up to 90 percent of instantaneous runoff and approximately 10 percent of total storm runoff.

Tsukamoto et al. (1982) determined that pipes provided almost 100 percent of discharge monitored in an excavated trench in a small forested basin in Japan. Mosley (1979, 1982) applied water to forested hillslopes in New Zealand and measured timing and volume of response at exposed soil faces downslope. Mosley interpreted subsurface discharge to be the most important source of runoff for all but smaller events, and concluded that pipe discharge was an important component of subsurface discharge. In the latter effort, Mosley reported that macropore networks rapidly conveyed up to 40 percent of the water applied upslope of the soil faces.

Observations of pipe and matrix discharge in the examples just cited have, in almost all cases, utilized trench excavations as a part of the experimental design. Though this technique is the most practical for intercepting and measuring pipe and matrix discharge, it does create an artificial face that disrupts normal subsurface discharge patterns (JeJe et al. 1986). Atkinson (1978) discussed this situation, indicating that the consequence of creating a free face is the reduction of unsaturated throughflow and the artificial buildup of a saturated wedge. It is not clear to what extent the measurement bias introduced by this technique affects conclusions that might be drawn about the importance of pipe discharge relative to other storm runoff flowpaths.

For pipe discharge to be an important component of storm runoff, pipes must not only capture a substantial amount of storm precipitation, but must also be capable of rapidly routing captured water downslope. Jones (1981, 1987) reports that pipe velocities measured by various researchers averaged 0.1 m/s, and ranged as high as 0.8 m/s. These velocities equal or exceed overland flow velocities, and are much faster than matrix velocities, which Jones reports as typically on the order of 0.00006 to 0.025 m/s (Jones 1981).

In a similar manner as previously noted for general storm runoff processes, volume and timing of pipe discharge appears to be related to antecedent soil moisure status at the onset of any additional precipitation (Beven and Germann 1982, Jones 1979, Wilson and Smart 1984). Studies of pipe hydrology have identified thresholds of precipitation and/or soil moisture status required before pipes initiate a discharge response (Jones 1987, McCaig 1983), or begin to discharge in a manner linearly related to additional rainfall inputs (Wilson and Smart 1984). Also, different pipes at the same measurement location may respond differently under any given antecedent condition, and the discharge from any particular pipe (or pipe network) will vary from storm to storm (Jones 1979).

Combined antecedent soil moisture and storm event precipitation thresholds may reflect a requirement for saturation of subsurface materials surrounding pipes in order to trigger appreciable pipe discharge (Dunne 1978, Jones 1981). McCaig (1983) points out that this threshold represents a lag factor that depends on 1) infiltration processes, 2) raising the water table to a critical level where water can freely enter pipe cavities, and 3) allowing transmission time through pipes to efflux points (especially for smaller pipes).

McCaig is vague in interpreting the "critical level" which is required for pipe discharge to occur. In fact, he states that pipe discharge can occur without saturated conditions, and Whipkey (1969) and Aubertin (1971) claim to have observed pipe discharge through zones of unsaturated materials. One possible explanation for this is that once water enters a pipe through an interface with saturated materials, high transport velocities and lower-permeability pipe walls along the length of the pipe could combine to minimize seepage back into the surrounding, unsaturated matrix. Consistent with this, Aubertin observed that many old root channels at his study site were lined with woody remnants and that some were lined with an impervious layer of decomposed organics and deposited clay particles.

Whether or not pipes require saturated conditions to deliver appreciable amounts of water downslope, those studying pipe hydrology seem to concur that pipes have the potential to generate substantial storm runoff, especially where precipitation is combined with wetter soil moisture conditions. However, some of these authors have noted a limiting aspect of pipe discharge contribution to storm runoff. In large storm events, or where antecedent soil moisture conditions are high at the onset of a storm event, pipe discharge can become less important to overall runoff response as other runoff generating mechanisms become active (Jones and Crane 1984, Jones 1987).

Other authors have altogether questioned the hydrologic importance of pipe discharge to storm runoff generation in humid regions. Researchers studying throughflow discharge in an area near Mosley's (1979, 1982) field site questioned his interpretation of the significance of pipe discharge (Sklash et al. 1986, Pearce et al. 1986). They used hydrometric and natural tracer techniques to examine runoff contributions from "new" water (that associated with the storm event triggering surface runoff) versus "old" water (pre-event subsurface water mobilized by additional inputs of soil water). The concept that new water passes through the subsurface environment like a wave, displacing old water which is then pushed ahead to rapidly become surface discharge, was first described by Hewlett and Hibbert (1967) and termed "translatory flow."

Reporting on different aspects of the same research, Sklash et al. (1986) and Pearce et al. (1986) concluded that old water provided 60 to 70 percent of surface runoff from hilltop ridges and 90 percent of surface runoff from valley areas at their study location. Since pipe discharge is often described as a potentially rapid and efficient runoff routing system, they concluded that the lack of new water delivery downslope signifies that pipes are not operating in a hydrologically important manner. The question as to whether pipe discharge could also serve as a conveyance system for old water as well as new water was not addressed by the researchers.

A similar, yet separate phenomenon by which old water is considered potentially important in triggering a rapid runoff response is termed "transient flow." Transient flow is generated when water--stored in the capillary fringe under tension, but at near-saturated conditions--is suddenly released after addition of a small amount of new water (Gillham 1984). According to Gillham, this can result in a rapid and substantial rise in the water table, especially under conditions where the capillary fringe prior to the storm event extends nearly to the ground surface. The generation of transient flow could result in old water being directly converted to runoff, or could cause old water to saturate streamside zones so that new water rapidly becomes runoff through saturated overland flow. Bernier (1985) cites results from several tracer studies to suggest that old water can provide 50 to 80 percent of peak storm discharge and runoff volume.

Though Gillam (1984) does not address the issue, it is possible that transient flow rather than piping is responsible for rapid subsurface discharge in some cases. However, where transient flow is an important mechanism, Reven and Germann (1982) contend that rapid downward movement of storm water as pipe discharge (ahead of the wetting front in the surrounding matrix) could result in a more rapid transient flow response than would otherwise occur.

Understanding the importance of pipe discharge to hillslope runoff generation will ultimately require accurate conceptual arid quantitative models of pipe hydrology. As previously mentioned, Carson and Kirkby (1972) and Gregory and Walling (1973) provided early attempts at constructing conceptual models. Wilson and Smart (1984) and Jones (1987) presented conceptual models of pipe hydrology for their study sites. Jones also attempted to quantify transfer process and storage reservoir model components based on data collected at his field site. Dunne (1983) concurred that pipe discharge needs to be, incorporated into theories of storm runoff generation, but indicated that more knowledge through field experience is required before this can happen. Consistent with this, McCaig (1983) reports that few attempts at modeling pipe discharge have been undertaken.

Runoff prediction models currently used for humid regions may not be appropriate for cases where pipe discharge is an important component of storm runoff. Some of the commonly used models are based on Horton's (1933) early concept of runoff generation (e.g., the Rational Method), though these are generally inadequate in explaining the dynamics of runoff generation (Dunne 1983, Bernier 1985). Other models attempt a more realistic portrayal of runoff dynamics by using an adaptation of Darcy's Law to model transient flow through saturated-unsaturated zones in the subsurface environment (Bernier 1985, Dunne 1983).

The latter modeling approach can provide reasonable results where subsurface discharge occurs primarily through the soil matrix, but has been demonstrated to be inaccurate in field and laboratory experiments when pipe discharge occurs (Seven and Germann 1982). There are two primary reasons why pipe discharge can not be well-represented using a model based on Darcy's Law. First, pipe discharge is often turbulent due to flow channelization and the typically irregular nature of pipe shape and direction along the. course of travel (Jones 1981). Contrary to this, Darcy's Law assumes laminar diffuse flow (Whipkey 1967). Second, piping creates a condition of variable permeability, with pipes usually having much higher hydraulic conductivity than the surrounding matrix. Darcy's Law assumes uniform permeability, or at least, requires a value representative of overall conditions (Sloan and Moore 1984).

Where pipes occur extensively and are hydrologically active in a natural. landscape, the usefulness of Darcy's Law for modeling subsurface water transport maybe compromised. In such cases, water rapidly moving through pipes could cause an earlier and flashier runoff peak than might otherwise be expected, and total volume of storm runoff generated by the subsurface environment could be greater than expected.

Study Objectives

Pipes that are presumed to be of naturally occurring origin exist within headwater-positioned swales in the North Fork Caspar Creek watershed near Fort Bragg, California. During three storm seasons, discharge was measured from pipes at outlets in excavated trenches or headwalls of gully features at a single transeet across each of three swales. Rainfall and surface channel discharge data are available for the same study area, and over the same. time period and with similar time resolution, as data collected for pipe discharge.

No overland flow was observed in swale axes above transact locations during the study period, indicating that subsurface runoff was probably the only storm runoff mechanism active in the study swales during this time. A preliminary review of pipe discharge data suggested a flashy and large magnitude response visually similar to that obtained for stream channel MUN.

A comparison of concentrated subsurface (pipe) versus surface channel discharge magnitude and timing characteristics was considered to be useful. If there was a general similarity, subsurface discharge could be considered being concentrated and rapidly routed by mechanisms more consistent with models of channelized surface discharge than models of conventional (matrix) subsurface discharge. Similarly, if a uniformly applied runoff-measurement technique indicates that pipe and surface channel runoff are of similar magnitude during storm events, it would then be reasonable to interpret pipe runoff as an important source of storm runoff from the study swales.

The analysis was conducted by comparing, for the same storm events, hydrographs representing the sum of all measured pipe discharge at each study transact (i.e., pipe transect discharge relative to the hydrograph of surface channel discharge generated from a small watershed that contains one of the swales and is located in close proximity to the other two. In particular, the hydrograph comparisons were based on timing, instantaneous unit-area discharge, and unit-area runoff characteristics ,for the three pipe transacts and the comparison stream channel.

STUDY AREA

The general study area has been described by Keppeler (1987), and some of the specific study sites have been described by Ziemer and Albright (1987). Much of the discussion in this section is taken from these two sources.

The study area is the 508-ha North Fork Caspar Creek Experimental Watershed in the Jackson Demonstration State Forest near Fort Bragg, California (Figure 1). The area has youthful topography, consisting of uplifted marine terraces that date to the late Tertiary and Quaternary periods (Kilbourne l9$6). Hillslopes are moderate, ranging from approximately 20 to 80 percent, with elevation of the North Fork watershed ranging from 37 to 320 meters.

The study sites are located in the uppermost portion of the North Fork Caspar Creek watershed (Figure 1), where evidence of piping is common. Evidence of piping includes: locations along swale axes where the ground surface has collapsed into what appears to have been intact and hydrologically active pipes; discontinuous gully ("blow out”) features that are connected by pipes routing through intermediate land bridges; pipe outlets positioned in gully headwalls or in the banks of perennial and ephemeral channels; pipe outlets positioned along the floor of headwater swale axes (but upslope of established surface channels). Pipe outlets sometimes have sediment aprons near the point of efflux, and a number of pipe outlets have

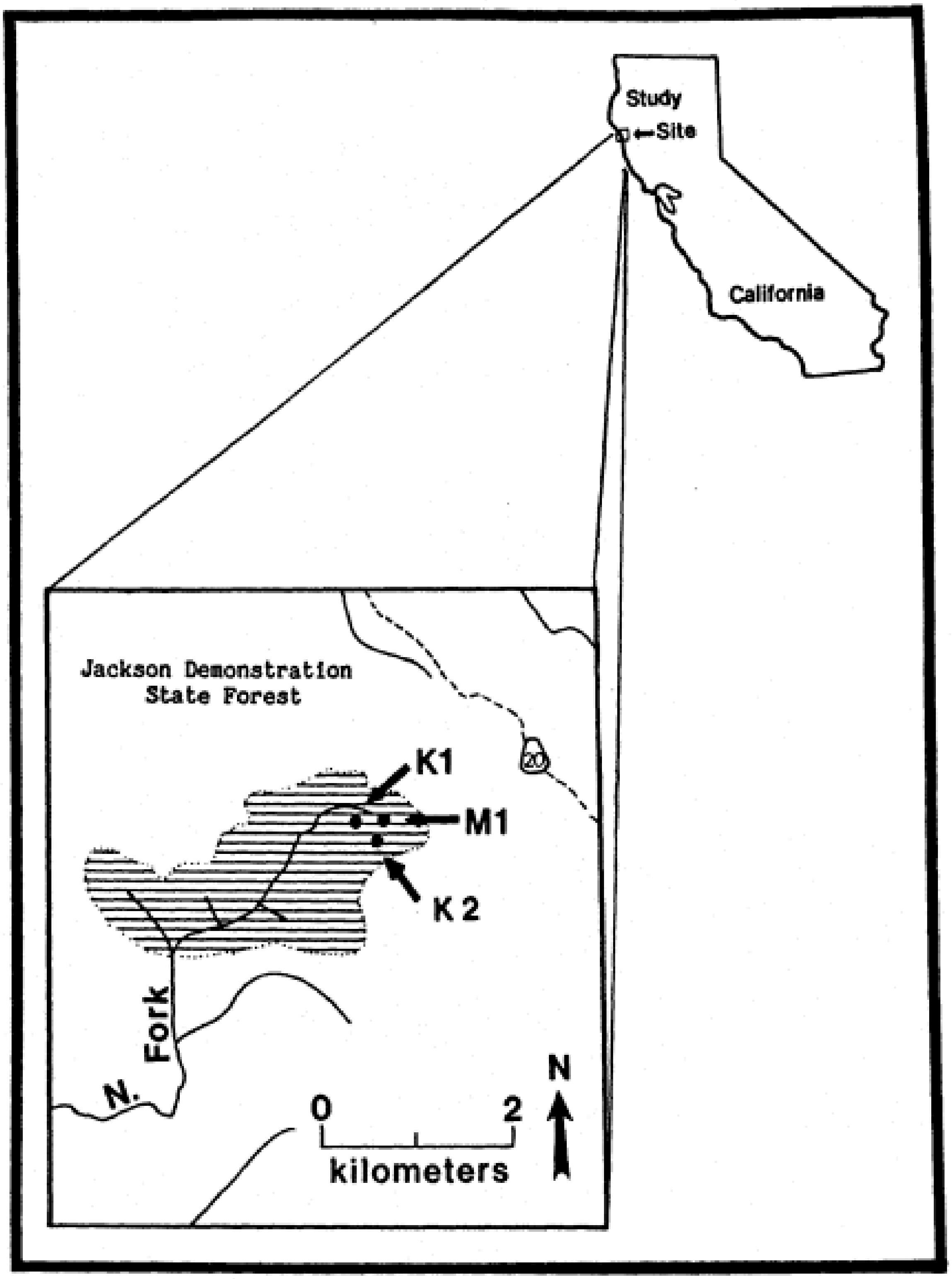


Figure 1. General Location of Pipe Discharge Study Sites (After Ziemer & Albright, 1987).

been observed to discharge appreciable amounts of water and sediment during rain events when soil conditions were at least moderately wet.

Overstory vegetation in the Caspar Creek Experimental Watershed is dominated by stands of second-growth Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) and coast redwood (Sequoia sempervirens (D.Don) Endl.) having an average density of 700 m^3/ha. Understory vegetation includes brush species such as evergreen huckleberry (Vaccinum ovatum Pursh), Pacific rhododendron (Rhododendron macrophyllum D.Don) and sword fern (Polystichum munitum (Kaulf.) Presl.). Most of the original old-growth was removed by clearcut logging operations in the late 1800's. Since that time, the North Fork watershed has remained largely undisturbed.

The climate of the study area is characterized by low-intensity rainfall and prolonged cloudy periods in winter and relatively dry summers with cool coastal fog. Mean annual precipitation at Caspar Creek is approximately 1190 mm, with 90 percent of this annual precipitation occurring between the months of October and April. Snowfall is rare in the study area. Temperatures are mild due to the moderating effect of the Pacific Ocean.

The three piping study swales (M1, K1, K2) are small zero-order basins located in headwater-positions in the North Fork Caspar watershed (Figure 1). The swales have slopes ranging from 30 to 70 percent, and are located in an elevation range of 100 to 320 meters (Figures 2, 3, 4). The soil at the study swales is classified as the Vandamme soil series, derived from sedimentary rocks of the Cretaceous Age (primarily Franciscan graywacke sandstone). The depth to paralithic contact is generally 100 to 150 cm with soil particles

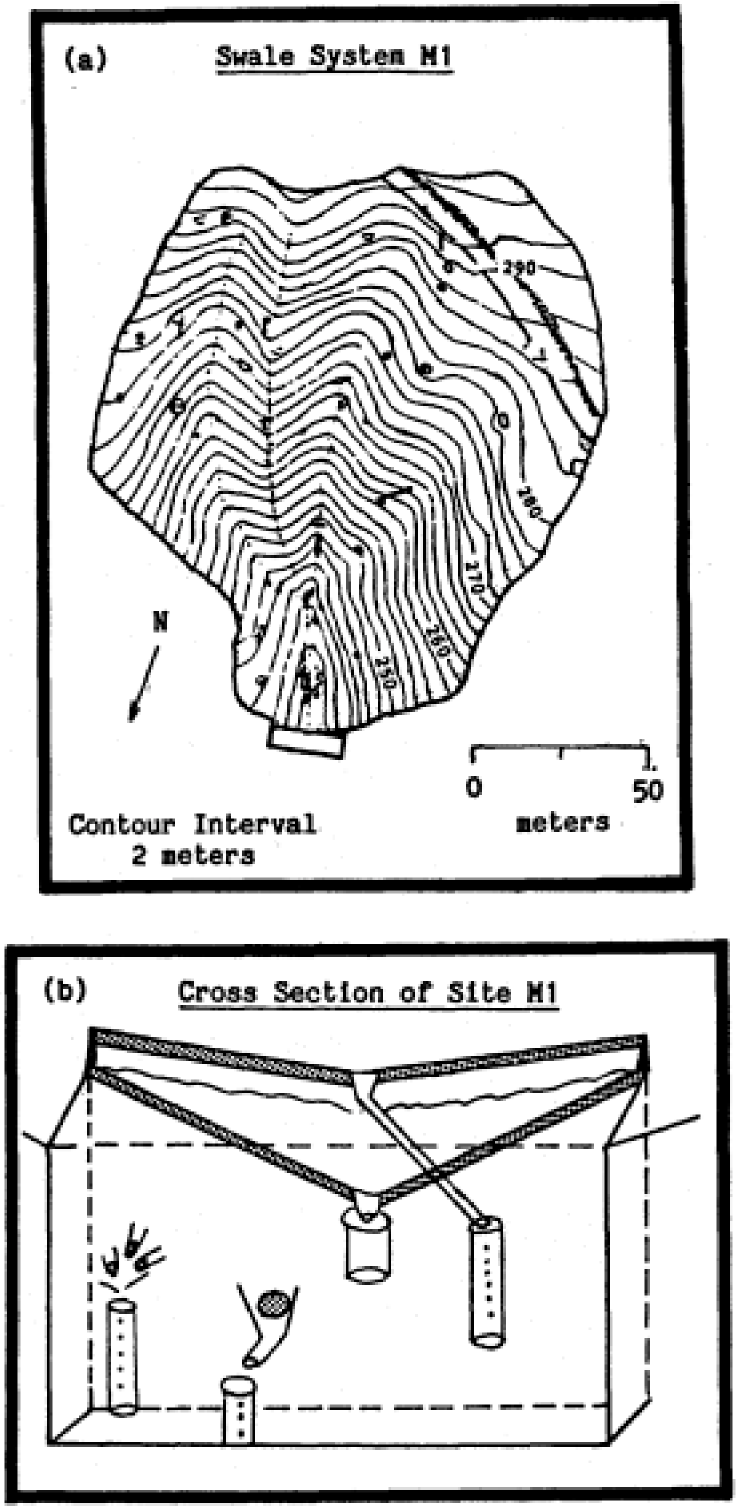


Figure 2. Study Site M1: (a) Swale System, (b) Cross Section of Pipe Discharge Measurement Location (After Ziemer & Albright, 1987).

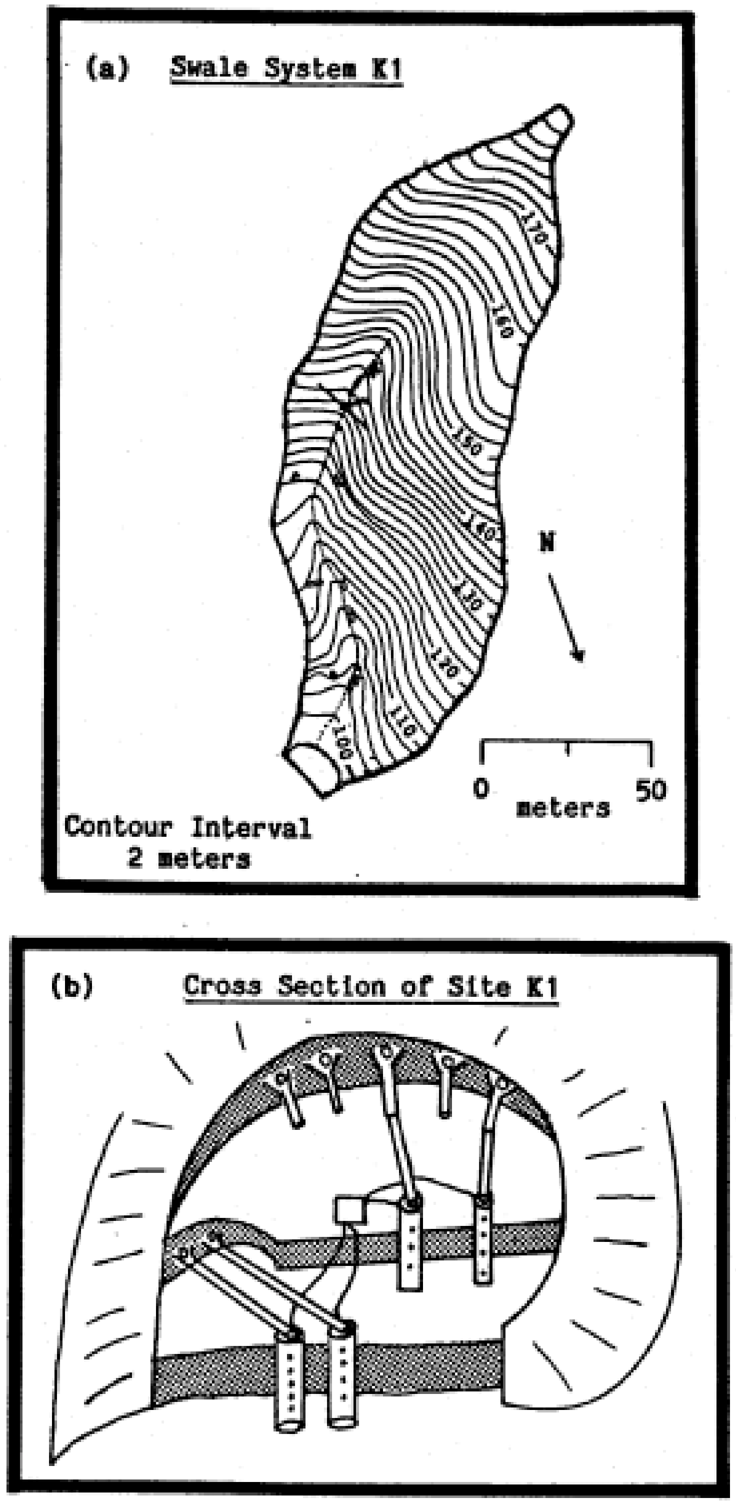


Figure 3. Study Site K1: (a) Swale System, (b) Cross Section of Pipe Discharge Measurement Location (After Ziemer & Albright, 1980.

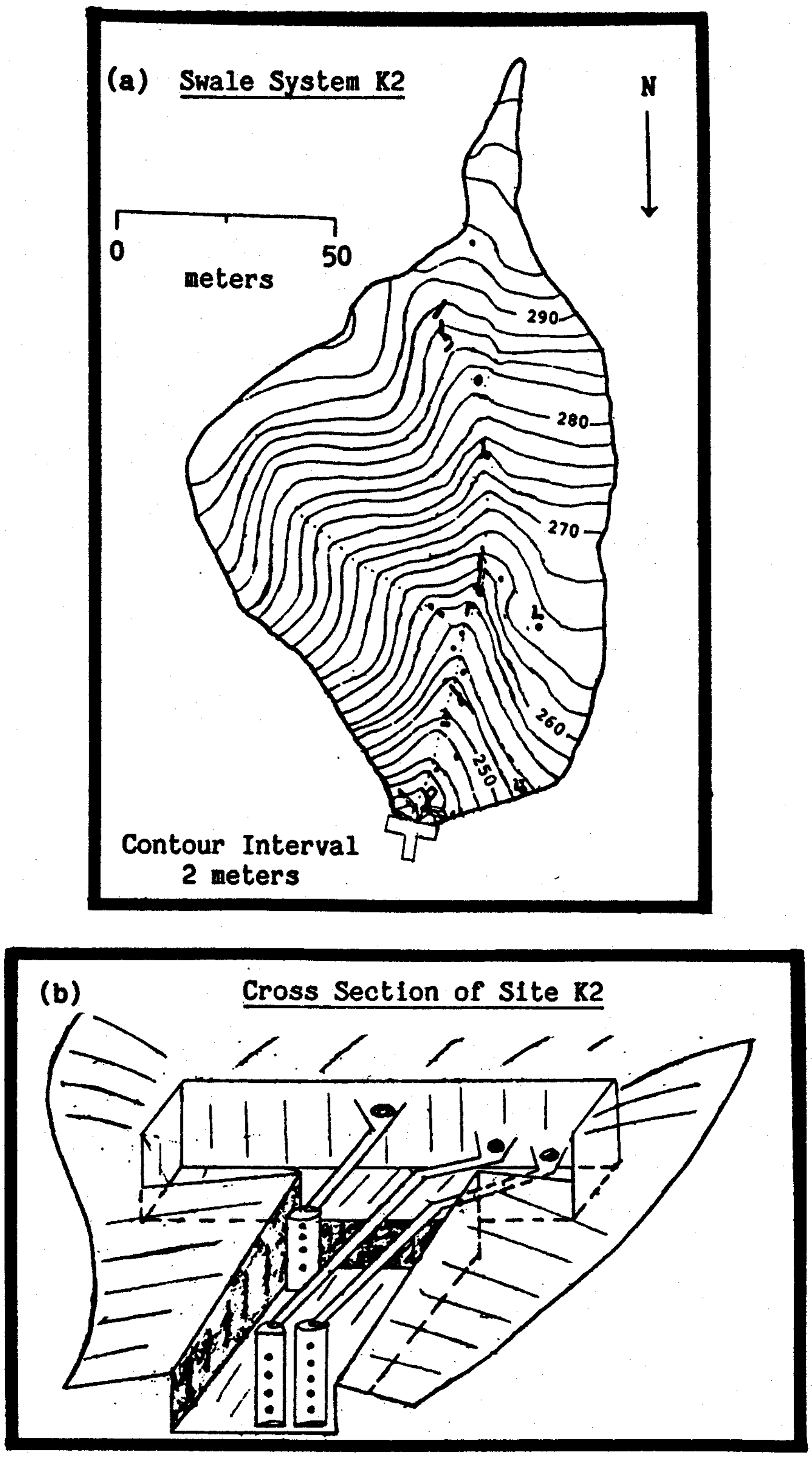


Figure 4. Study Site K2: (a) Swale System, (b) Cross Section of Pipe Discharge Measurement Location.

ranging from 35 to 45 percent clay and 0 to 10 percent gravel. The Vandamme soil series is characterized as having very slow infiltration rates and moderately slow subsurface transmission rates.

The three study swales are in close proximity to each other (Figure 1). One measurement transect was developed for each of the study swales at a location where pipe discharge already exited to the ground surface, and where no appreciable opening (breakthrough) of the pipe feature to the ground surface could be detected upslope of the transect. Each transect was created by excavating material to create an exposed soil face across the axis of the swale, though the excavations did not completely cut across the swale floors.

Pipes exposed in the excavated headwalls did not occur at any consistent level or position, but all were within the approximately two meter deep soil profile. Pipe diameters ranged from 1 to 60 cm. Pipe discharges measured at the three sites varied from steady dripping to a peak of over 500 l/min from a single pipe during storm runoff.

The M1 pipe discharge measurement location (Figure 2) is located in the central axis of the 1.14-ha M1 study swale, at the upper end of a gully that marks the beginning of channelized surface discharge. Pipe discharge measured at this transact includes pipe M106, an approximately 80 cm (height) by 60 cm (wide) pipe at its exposure in the trench face, and which provides at least 90 percent of pipe discharge from the swale during storm runoff. M106 is a perennially discharging pipe, though summer baseflow often drops to less than 1.0 l/min. The base of pipe M106 is nearly 2 m deep, the base of the pipe also representing the interface between the upper soil material and a lower gleyed-clay layer. Also at transact M1, a cluster of small (2 to 4 cm) pipes in close proximity, all 0.5 m or less below the ground surface, were collectively measured as pipe M190. Finally, at the M1 transact, metal flashing arid discharge measuring equipment were installed to separately monitor matrix seepage through a colluvial wedge and overland surface channel flow.

The K1 pipe discharge measurement location (Figure 3) is located along one side of the 1.0-ha K1 study swale axis, at a previously existing gully headwall with three natural terraces. Hydrologically active pipes occur along the upper two terrace levels. Pipes at this transact include K101, a flashy, ephemeral pipe about 1.5 m deep in the soil profile on the middle terrace (data from K101 was not used in this study due to repeated instrumentation problems), and K102, the largest discharging pipe at transact K1, located on the same terrace as, and immediately adjacent to, K101. Like M106, K102 maintains a baseflow during much of the winter rainy season, though K102 ceases discharging long before M106 during dry periods. Pipes K105 and K107, located within 0.5 m of the ground surface on the upper terrace, are ephemeral pipes with flashy response during storm events. Other pipes at transact K1 were not measured on a regular basis, but did not appear to provide significant storm discharge during the 3-year study period. All of the pipes at this transact are between 10 to 20 cm in diameter.

The K2 pipe discharge measurement location (Figure 4) is located along the axis of the 0.85 ha K2 study swale axis. A blow-out feature previously existed along one side of the swale axis, but the pipes exposed at this transact continued downslope through a land bridge before emerging as surface channel discharge about 10 m downslope. Other than at the blow-out, the 2 m deep trench excavated across the swale at this transact exposed a previously undisturbed swale floor. There are three pipes at the K2 transact. K201 is the largest pipe, similar to M106 and K102 in that it maintains a baseflow for some time during dry periods. When K201 baseflow does cease, it is usually after K102 dries up, but before M106 dries up. K201 is approximately 50 cm in diameter, and is located about 1.0 to 1.5 m below the ground surface. A mixed clay arid broken shale layer is evidenced within 0.5 m below the outlet of K201 in the trench face. K202 is a pipe adjacent to K201, at about the same elevation but approximately one-half the size, that yields a subdued response during storm events and maintains a trickle base flow during much of the time that K201 also maintains a baseflow. Finally, K103 is a 15-cm diameter pipe within 0.5 m of the ground surface that is ephemeral, but very flashy during storm events.

The watershed used to provide discharge comparisons with the pipe transacts consists of an established stream gaging point (station MUN) that measures discharge from a 17 ha area that contains the M1 swale and is in close proximity to the K1 and K2 study swales. Topographic and vegetative cover conditions in the MUN watershed are very comparable to conditions in the three piping study swales.

METHODS

Study Time Frame

The M1 transect was equipped for data collection in late January, 1986, the K1 transect in early February, 1986, and the K2 transect in late March, 1986. Due to start up problems with site instrumentation, only partial data were collected for M1 and K1 during winter, 1986, and no data was collected for K2 until the start of winter, 1987. Partial or complete data was obtained for all three sites for storms during the period of winter, 1987, thru winter, 1988. A total of 22 storms were examined during the three-year period.

Field Techniques

Discharge from individual pipes was captured at pipe outlets in excavated trench walls, then routed through a plumbing network into calibrated containers (acting as weirs) that allowed discharge measurements to be made.

Water was captured at pipe outlets using angular or circular-shaped metal flashing driven into the soil wall around the pipe. The metal flashing was secured using a concrete mixture applied to a chicken wire framework that surrounded the flashing and was pinned to the trench wall. Water was conveyed from the flashing using combinations of large diameter plastic and flexible metal pipes to a connection at the top end of calibrated containers (one container per monitored pipe). At the top end of each container, a screen pouch was inserted to capture coarse sediment particles and organic debris, and a deflector baffle was also inserted to minimize splashing and pressure waves in the calibrated container due to water freely spilling in at the top.

The containers, constructed of PVC pipe, were 15 cm in diameter and 100 cm tall. Containers were mounted upright with the base capped and the upper end open and with holes and/or slots placed in a lengthwise pattern along the side. Containers were calibrated in the laboratory (with additional calibration points taken in the field) to allow derivation of separate stage-discharge relationships for each container.

Under field conditions, pipe stage (discharge) was monitored using pressure transducers mounted in the containers and a data logger which interrogated the transducers at 10-minute intervals.

Stream discharge at the MUN site was obtained using a Parshall flume and digital stage recording equipment operating at 10-minute intervals. However, the resulting electronic stream discharge record does not have data points at 10-minute intervals--only data points deviating from the last recorded data point by more than a threshold amount were recorded. Rainfall data were recorded as 5-minute depth totals at a location very close to the piping study swales using a tipping bucket raingage connected to an event recorder.

Data Reduction Procedures

All electronic data received from piping study transects and from the stream and raingage sites were plotted for review. Rainfall and stream discharge data were compared to similar data from other stations in the North Fork watershed, and some portions of the records flagged as "suspicious." Only minor modifications were necessary to reconstruct rainfall data.

Most modifications of MUN data were minor. However, MUN data required a potentially significant reconstruction for 13 storms (Storms 6-11 and Storms 16-22). in order to estimate timing and discharge for start of storm runoff. This information had to be reconstructed for cases where time gaps occurred in the data record. Time gaps resulted from software logic that was designed to save data memory during non-storm periods, or any other period when stream stage maintained a similar rate of increasing or decreasing stage.

The consequence of this was to create moderate-to-long time gaps (approximately 0.1 to 1 day for this study's data), especially during periods of relatively steady baseflow recession. The recorded data points that signaled an end to time gaps were often the first evidence of storm runoff as well. In many cases, runoff had commenced at some previous time, and from some lesser discharge, but was undetected due to software logic.

Reconstruction was done for cases where MUN hydrographs, in comparison with hydrographs for other nearby stream stations, looked suspicious at the period around start of runoff. For these cases, start of runoff was assumed to occur 10-minutes prior to the first evidence of MUN rise. This approach was used because HUM appeared to be flashy at start of runoff for many events. It was assumed that the typical overestimate of start time in the original data record may have been on the order of minutes, rather than hours. Discharge used for start of runoff was the last recorded discharge prior to the time gap which preceded evidence of a rise. This value was always lower than the value measured at the evidence of a rise, but certainly higher than the actual discharge at start of runoff.

Pipe discharge data was compared to discharge data collected for the same event at other pipes as well as at stream stations. Individual pipe discharge data flagged as suspicious were reviewed more carefully. Questionable data which could not be reconstructed or reasonably interpreted from the existing record were omitted from analysis. Significant data reconstruction issues are discussed later in this section.

After review and reconstruction of individual pipe discharge hydrographs, discharge measurements taken for all pipes at each transect were summed producing hydrographs that represented total pipe discharge measured at each transect for each storm event.

Data for the M1 and K1 transects had the following general problems during winter, 1986. Hydrograph traces produced for pipes at both sites displayed excessive "noise" caused by splashing and pressure waves in the calibrated containers. A data smoothing routine (3-point running average weighted to favor the point being smoothed) was used to reduce noise. Even so, additional data smoothing had to be done by plotting the hydrograph traces,. drawing visual best-fit lines through the traces, then interpreting timing, instantaneous discharge, and runoff volumes directly from the plot using a planimeter and a t-square. Also, the maximum peak discharge for Storm 2 for both M1 and K1 transect hydrographs were reconstructed by extending the recorded hydrograph limbs with dashed lines (Figures 7 and 8). These reconstructions were not used to provide data for maximum peak discharge, but were used to calculate total storm runoff, which was fudged to be less sensitive to imprecise reconstruction.

Data for all three piping transects had an ongoing problem throughout winter, 1987. The problem was caused by an operating error in the data loggers and resulted in irregular timing of data acquisition by the devices. The data loggers, which normally acquire data points at 10-minute intervals, failed to collect data for every interval during certain operating periods. An individual operating period is represented by the time between downloading of data from data loggers. Data processing identified periods having an incomplete data record, and also indicated the total number of missed intervals. However, the electronic file format output by data loggers made it impossible to determine where individual (or sequences) of missing data points occurred. Visual comparisons of plotted data for these periods indicated that the time-shift errors introduced by this problem were probably minor for most cases. No data were omitted from analysis for this reason.

Data for one pipe at each of the three pipe transects had an ongoing problem throughout winter, 1988. The problem was caused by a different type of data logger malfunction and resulted in a transformation of the signal received from the transducer before values were recorded by the data loggers. The recorded stage (discharge) values were thereby shifted from their actual value by a substantial amount. Comparison of discharge data for these three pipes with other pipe and stream discharge data considered of good quality clearly identified the periods when the malfunction occurred. Fortunately, a large number of manual discharge measurements were made during storm periods for the affected pipes. These manual measurements provided a basis for reconstructing these file periods. Data for part of one storm at one site (Storm 21 at Site K1) was omitted from analysis for this reason.

Throughout the entire period of the study various problems occurred on an irregular basis that were related either to equipment design deficiencies, errors by field technicians, or outright equipment malfunction. Problems experienced during collection of field data include:

1. disruption of plumbing connections resulting in an undermeasuremept of pipe discharge;
2. malfunctions at the location of the calibrated containers, including--
   a. sediment or organic debris clogging at the top of the container, causing outsplashing and resulting in undermeasurement,
   b. plugging of container discharge holes and slots by debris, resulting in artificially high container stages and hence overmeasurement of discharge,
   c. use of a container designed for low discharges during large storm events, causing overtopping of the container and resulting in undermeasurement;

3. pressure transducer problems which include,
   a. long-term drift, reducing accuracy by introducing noise or shifting data values,
   b. electrical shorting, causing complete loss of data.

These problems were addressed as identified, and the affected data were reconstructed. The most serious occurrences of these problems caused data to be eliminated from the record.

Finally, discharge from pipe K101 (a flashy, ephemeral pipe that provided 15 to 30 percent of total discharge at the K1 site during peak storm periods) was not included in the summation of K1 transact discharge for the entire period of study due to repeated instrumentation problems associated with this pipe.

Plots indicating stream discharge, pipe transact discharge, and cumulative rainfall and rainfall intensity are attached as appendixes. Plots for Storms 1 to 3 are included as Appendix A (Figures 6-9), Storms 4 to 6 as Appendix B (Figures 10-14), Storms 7 to 10 as Appendix C (Figures 15-19), Storms 11 to 14 as Appendix D (Figures 20-24), Storms 15 to 19 as Appendix E (Figures 25-29), and Storms 19 to 22 as Appendix F (Figures 30-34). Periods of data eliminated from data files prior to analysis appear as gaps in the plotted records.

Analytical Procedures

The objectives of this study are: 1) to determine if pipe (concentrated subsurface) discharge at study swales occurs with similar magnitude and timing as discharge at a nearby surface channel, and 2) interpret whether pipe runoff provides an important source of runoff from the study swales. The analytical approach to meet these objectives involves .a direct comparison of measured pipe and surface channel discharge and other runoff characteristics during storm events.

The analytical approach was developed through the following reasoning. Pipe runoff measured at the excavated transects was treated as an (conservative) estimate of the magnitude and duration of total storm runoff from the study swales. This is reasonable since there was no evidence of overland flow in swale axes above transect locations in the study swales, or evidence of appreciable matrix seepage from the excavated trench faces during the three storm seasons included in this study. Surface channel runoff measured at station MUN is also a measure of total storm runoff from the study area, but at a larger spatial scale. Surface runoff measured at MUN probably includes contributions from both subsurface and saturation overland flow mechanisms.

A preliminary review of pipe discharge data suggests a flashy and large magnitude response visually similar to that obtained for stream channel MUN. It would be useful to determine if these responses are indeed similar in form and (or) timing. If they are, subsurface runoff is being concentrated and rapidly routed by mechanisms more consistent with models of channelized surface discharge than models of conventional (matrix) subsurface discharge. Similarly, if a uniformly applied runoff-measurement technique indicates that pipe and surface channel runoff are of similar magnitude during storm events, it would then be reasonable to interpret pipe runoff as an important source of storm runoff from the study swales.

Hydrographs of pipe transect and surface channel discharge for the three-year period of the study were inspected for similarities. A total of 22 storms during this period were included in the analysis based on the presence of a runoff response and acceptable data quality for the stream discharge site and at least two of the three pipe transects. However, not all data was used for each site for all 22 storms. Most of the data omissions were due to problems with pipe discharge data as previously reported, but data for portions of individual storms were not used due to incompatibility issues. For example, maximum peak discharge comparisons were not made for Storm 6. This storm was a complex event that had a comparably different peak at MUN relative to two of the pipe transects. MUN data is coded as "missing" for this case.

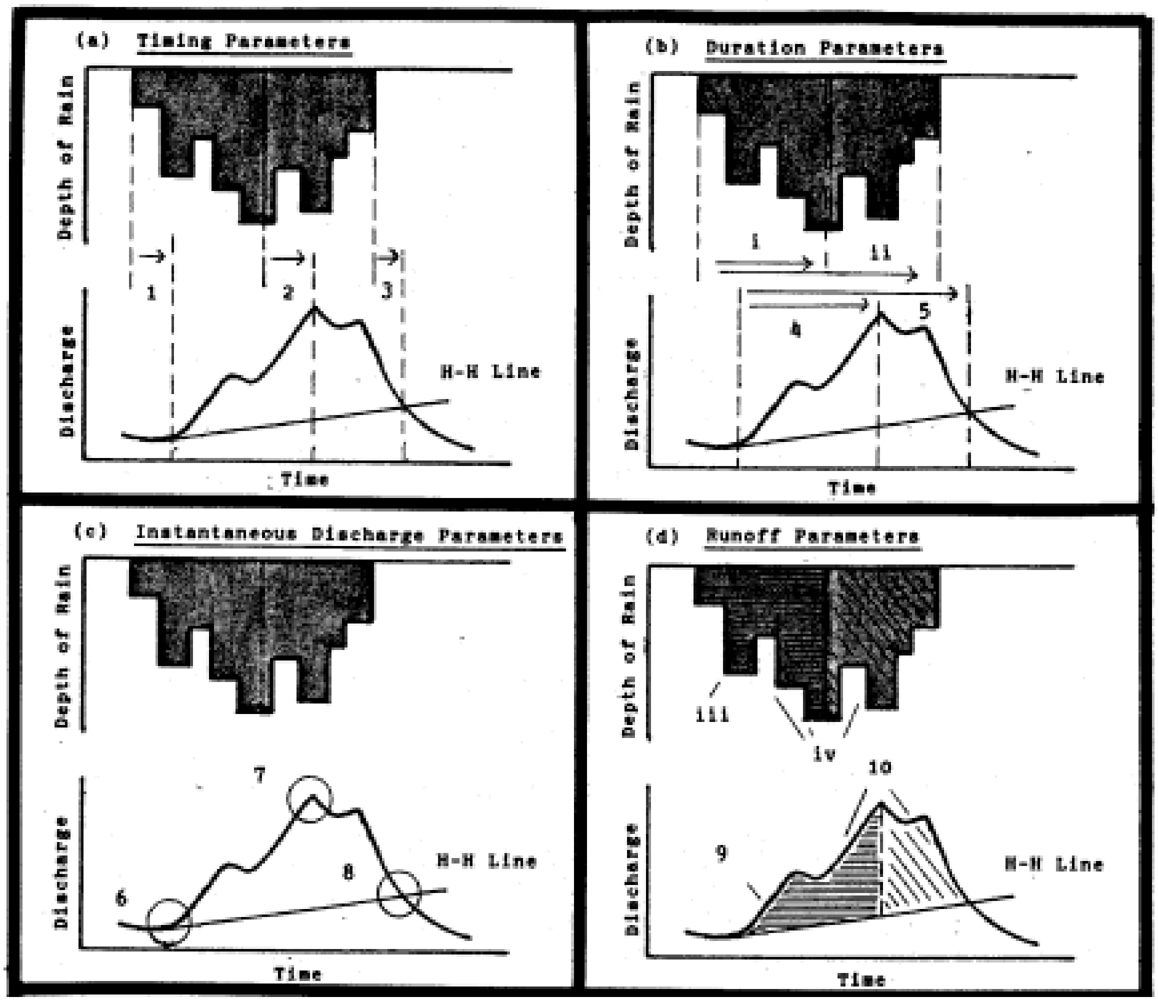
Hydrograph characteristics were measured to allow comparison of pipe transect and stream discharge response in four categories: timing, duration, instantaneous discharge, and cumulative runoff. Three timing characteristics (hereafter termed "parameters") were selected for each storm hydrograph: time at start of storm runoff, time at maximum peak discharge during storm runoff, and time at end of storm runoff. All of these were expressed as lag times relative to analogous rainfall hyetograph times (explained below). Two duration parameters were selected for each storm hydrograph, these being time from start of runoff to maximum peak discharge and time from start of runoff to end of storm runoff. Three instantaneous discharge parameters were selected. These were unit-area discharge at each of the start of storm runoff, maximum peak discharge, and end of storm runoff. Two runoff parameters were selected for each storm hydrograph. These were cumulative unit-area quickflow runoff from start of storm runoff to maximum peak storm discharge, and from start of storm runoff to the end of storm quickflow runoff.

Determination of time at end of storm runoff, as well as volume of storm runoff was done using Fortran 77 programs that incorporated the Hewlett and Hibbert (1967) hydrograph separation technique. This technique, hereafter referred to as the "H-H method", is commonly used in hydrographic analysis. The H-H method provides an arbitrary, but consistent, basis to separate storm quickflow runoff and delayed flow (baseflow) using a separation line (the "H-H line"). Given a plotted storm hydrograph, the H-H line begins at the start of a storm runoff response, then rises during the storm period at a rate of 7.87 l/min/ha/day. The end of the storm runoff period is determined as the point where the H-H line intercepts the recession limb of the hydrograph. Quickflow runoff values are interpreted as the area (volume) of runoff below the hydrograph trace but above the H-H line and baseflow is represented by the area below the H-H line.

This H-H line rising rate was selected to be consistent with the value initially proposed by Hewlett and Hibbert (1967) and used since by other researchers in various settings. This same rate of rise was also used in previous work done at the Caspar Greek study area (Thomas 1986). Inspection of data used in this study indicates that, for most storm events at all study sites, the H-H line contacts the hydrograph recession limb in the vicinity of the inflection point that signals a decreasing rate-of-decay of the recession limb. Most of the runoff associated with the rainfall event has occurred by this time. For two of the 22 study storm events (Storms 11 and 17), end of storm parameter comparisons were not possible because the H-H line did not intersect the comparable recession limb for all sites.

Rainfall data was also summarized for each storm event. Rainfall timing data was used as a basis to calculate lag time parameters for the pipe transect and stream discharge sites. Rainfall data used in this regard were: time at start of sustained rainfall (prior to start of runoff), time at median rainfall (the time associated with the midpoint of cumulative rainfall for each storm event), and time at end of sustained rainfall (the time of the last sustained rainfall prior to the end of the runoff event for at least most or all of the discharge measurement sites). Other rainfall data were summarized and reported, but ultimately were not used in the analysis. These data were: duration from start of sustained rainfall to each of time at median rainfall and time at end of sustained rainfall, and cumulative rainfall from start of sustained rainfall to each of time of median rainfall and time of end of sustained rainfall. Rainfall data was largely hand-calculated based on close inspection of rainfall data files.

Figure 5 provides a graphical representation of how rainfall data and hydrograph parameters were derived. The use of the H-H method to calculate time at end of storm runoff and volume of quickflow runoff is also represented in Figure 5. In addition, plots for all storms used in this study (Appendixes A-F) show an approximation of the H-H line for each storm. These lines were placed to be representative only. As previously indicated, the actual H-H



1- Lag Time from Start of Rainfall to Start of Storm Runoff
2- Lag Time from Time of Median Rainfall to Peak Discharge
3- Lag Time from End of Rainfall to End of Storm Runoff
4- Time from Start of Storm Runoff to Peak Discharge
5- Time from Start of Storm Runoff to End of Storm Runoff
6- Instantaneous Discharge at Start of Storm Runoff
7- Instantaneous Discharge at Peak of Storm Runoff
8- Instantaneous Discharge at End of Storm Runoff
9- Cumulative Quickflow Runoff from Start of Storm to Peak Discharge
10- Cumulative Quickflow Runoff from Start of Storm to End of Storm Runoff
i- Time from Start of Rainfall to Time of Median Rainfall
ii- Time from Start of Rainfall to end of Rainfall
iii- Cumulative Rainfall from Start of Storm to Time of Median Rainfall
iv- Cumulative Rainfall from Start of Storm to End of Rainfall

Figure 5. Representation of Storm Hydrograph Parameters: (a) Timing, (b) Duration, (c) Instantaneous Discharge, (d) Cumulative Rainfall and Quickflow Runoff.

line intercepts and calculations were done by computer manipulation of electronic files. The H-H line is not represented in the data plots for cases where the storm hydrograph is plotted at a very small scale.

Parameter values were tabulated for all storm events at each site and organized into data sets. Every parameter was represented by three data sets. Each data set for a parameter contained the same values for MUN as well as values for one of the three pipe discharge transects for the 22 storm events. Data values that were missing or could not be reconstructed were coded as '*'.

Data treatments were applied to all three data sets for each parameter. The data treatments were:

1) taking the difference between the values obtained for the pipe transact and those at the stream site for all eases (storms) where point observations existed in the data set;

2) taking the difference between the log-transformed values at the pipe transect and the log-transformed values obtained at the stream site for all cases where joint observations existed in the data set;

3) calculating the ratio of the values obtained for the pipe transect relative to those values obtained at the stream site for all cases where point observations existed in the data set.

Each treatment of a data set produced an array of values. Each array of values is termed a "variable" in this study. Since there were three data treatments applied to each of three data sets for each of 10 parameters, a total of 90 variables were produced.

The first data treatment reflects the underlying assumption that the responses at the pipe transects and the stream site should be directly comparable, and that parameter values for each site should reflect a linear response over the range of observed storm events. The second data treatment reflects the underlying assumption that while the responses at the pipe transects and the stream site should be directly comparable, the parameter values for all sites should reflect an exponential response over the range of observed storm events. The third data treatment reflects the underlying assumption that the responses at pipe transects and the stream site are not comparable on a simple linear-additive scale, but rather that the relative change in parameter value response over the range of observed storm events is directly comparable.

The spread and distribution of values contained in each variable was then examined using dotplots, which are horizontal data displays similar to histograms. Individual dots along ,the horizontal axis of the plots represent single values of data. Dotplots for the variables selected for hypothesis testing are attached as Appendix G. The variable that demonstrated the best symmetrical-appearing distribution for each parameter was selected for hypothesis testing.

Hypotheses testing used a form of the t-test for paired-comparisons. A total of 30 t-tests were conducted. Each t-test evaluated a single variable. Thus, the tests were implemented as one-way t-tests. Calculation of test statistic values used the formula:

$$T = \frac{(\bar{x} - \mu)}{\frac{sd}{\sqrt{(n-1)}}}$$ where;

$\overline{x}$ = sample mean,

sd= standard deviation of the sample,

n= sample size,

μ = hypothetical population mean.

The value of the hypothetical population mean was determined by the variable selected for testing. For parameters where the variable was constructed using Data Treatment 1 or 2, the hypothetical mean had a value of zero. For parameters using Data Treatment 3, the hypothetical mean was equal to one. For each test, the hypothesis was that there was no significant difference in observed or treated data for one of the pipe transects less the comparable observed or treated data for stream channel MUN.

The study goals and methods were organized as a general investigation of the similarity of concentrated subsurface and surface channel runoff and other discharge characteristics. Therefore, pipe transect data from all three study swales for a common parameter-were considered as a "family" of related "statements" in the context of terminology and methodology described by Miller (1981). Since there are 10 study parameters, this resulted in 10 families of statements.

This influenced the interpretation of significance values obtained for each test result. Significance was determined using the Bonferroni multiple comparison method applied to families containing three tests each, with a family error rate for determination of significance set at the five percent level (Miller 1981). Each family compares MUN to pipe transects M1, K1, and K2 for a single parameter using a significance level of 0.05/3 = 0.0167 = $alpha_{(I)}$ for each individual test. Setting the determination of significance for each statement$_{(I)}$ in a family at this level provides, for the consideration of the family as a whole, an expected Type I experimental error rate of no greater than five percent. That is, the procedure limits to five percent the probability of rejecting at least one of the three null hypotheses in a family given that all are true.

RESULTS

Study Data

Instantaneous discharge and timing parameter data for pipe transects and MUN at start of runoff events are reported in Table 1. Data for the sauce parameters at maximum peak discharge during runoff events are reported in Table 2, and at end of storm runoff in Table 3. Rainfall data used to develop timing parameters are also reported for start of storm (Table 1), median of cumulative storm rainfall (Table 2), and end of storm (Table 3).

Duration parameter data for pipe transects and MUN are reported in Table 4. These include data for duration from start of runoff to maximum peak discharge, and for duration from start of runoff to end of runoff. Duration data for each site is referenced to time at start of runoff at that site. The values reported in Table 4 are calculated from timing data reported in Table 1, Table 2, and Table 3. Duration information for storm rainfall is also reported in Table 4, though this information was not used in the analysis.

Cumulative unit-area quickflow runoff for pipe transects and MUN are reported in Table 5. These include cumulative runoff from start of runoff to maximum peak discharge, and for start of runoff to end of runoff at each site. Cumulative rainfall information is also given in Table 5, though this information was not used in the analysis.

Table 1. Starting Data for Storm Events, Including Rainfall Beginning Date and Time, Lag Time from Beginning of Rainfall to Beginning of Runoff at Study Sites, and Unit-area Discharge at Beginning of Runoff at Study Sites.

	Rainfall		MUN		M1		K1		K2	
Storm Number	Date	Time (hhmm)	Lag (min)	Discharge (L/min/ha)	Lag (min)	Discharge (L/min/ha)	Lag (min)	Discharge (L/min/ha)	Lag (min)	Discharge (L/min/ha)
1	02/13/86	1850	330	10.6	310	10.4	175	10.0	*	*
2	03/06/86	2350	390	7.0	460	4.2	685	1.0	*	*
3	03/14/86	1800	490	52.9	735	47.2	855	28.0	*	*
4	12/19/86	815	114	1.0	145	1.2	165	0.9	105	0.8
5	01/01/87	255	155	0.2	275	1.4	345	1.1	265	1.6
6	01/02/87	2105	325	12.7	285	6.2	445	4.7	435	7.4
7	01/23/87	1935	405	0.8	265	0.7	495	0.9	265	2.9
8	01/27/87	1455	135	18.8	155	9.0	395	9.9	155	9.3
9	02/01/87	2140	250	33.9	90	9.9	280	7.4	220	10.3
10	02/12/87	805	433	7.0	525	4.2	565	1.2	505	4.5
11	03/02/87	1620	250	10.6	220	1.7	420	1.0	590	5.2
12	03/04/87	1645	345	28.2	365	7.1	395	7.2	365	7.9
13	03/11/87	1840	530	24.7	480	6.5	480	3.7	*	*
14	03/20/87	1900	460	17.6	320	7.3	420	4.7	720	11.2
15	11/20/87	615	75	3.5	145	0.3	*	*	25	0.3
16	11/30/87	105	195	3.5	215	0.9	395	0.7	205	1.0
17	11/30/87	2115	445	3.5	695	0.3	445	1.1	435	3.4
18	12/06/87	225	175	45.8	135	45.2	175	14.3	85	14.6
19	12/07/87	2205	315	42.3	165	43.1	265	17.4	335	20.5
20	01/02/88	335	1515	7.0	1725	4.5	1935	4.3	2055	3.5
21	01/08/88	1250	1130	36.3	580	19.4	820	19.6	810	20.1
22	01/14/88	1715	245	24.7	185	17.0	295	11.2	205	43.0

Note: An '*' Denotes Missing or Questionable Data Not Used in Analysis

Table 2. Middle of Storm Data for Storm Events, Including Date and Time for Rainfall Median, Lag Time from Rainfall Median to Maximum Peak Discharge at Study Sites, and Maximum Peak Discharge at Study Sites.

	Rainfall		MUN		M1		K1		K2	
Storm Number	Date	Time (hhmm)	Lag (min)	Discharge (L/min/ha)	Lag (min)	Discharge (L/min/ha)	Lag (min)	Discharge (L/min/ha)	Lag (min)	Discharge (L/min/ha)
1	--	--	--	--	*	*	*	*	*	*
2	--	--	--	--	*	*	*	*	*	*
3	03/15/86	855	605	173	1040	139	725	92.0		
4	12/19/86	1035	216	17.6	85	12.0	125	7.1	365	11.8
5	01/01/86	745	235	63.5	285	27.8	355	32.9	375	34.7
6	01/03/87	615	*	*	1545	36.8	1585	38.9	1645	56.9
7	01/24/87	235	325	71.2	425	21.9	425	29.3	485	44.2
8	01/27/87	1730	740	60.0	1360	31.6	1150	43.1	950	43.3
9	02/02/87	225	245	157	895	88.7	575	85.2	945	100
10	02/12/87	1915	295	247	435	64.7	465	147.7	465	126
11	03/02/87	2020	610	38.8	440	6.7	1320	9.9	860	11.8
12	03/05/87	110	640	236	980	124.7	680	147.2	610	135
13	03/12/87	1110	220	258	570	145	290	167.2	*	*
14	03/20/87	2315	215	31.8	255	9.3	1615	16.9	945	17.3
15	11/20/87	740	10	7.1	350	5.0	*	*	250	2.4
16	11/30/87	525	215	28.2	*	*	225	8.0	75	13.6
17	12/02/87	750	3020	420	3040	316	2980	226.7	2940	324
18	12/06/87	500	200	173	770	94.2	470	111.9	360	126
19	12/09/87	1215	1125	416	1415	388	1155	206.1	*	*
20	01/03/88	1640	440	190	990	90.3	620	103.9	500	78.7
21	01/09/88	1635	1745	141	2505	117	*	*	*	*
22	01/14/88	2220	240	116	1030	72.8	660	75.8	860	116

Note: An '*' Denotes Missing or Questionable Data Not Used in Analysis; '--' Indicates Data Not Measured Since All Corresponding Pipe Data Was Missing

Table 3. Ending Data for Storm Events, Including Rainfall End Date and Time, Lag Time from End of Rainfall to End of Runoff at Study Sites, and Discharge at End of Runoff at Study Sites.

	Rainfall		MUN		M1		K1		K2	
Storm Number	Date	Time (hhmm)	Lag (min)	Discharge (L/min/ha)	Lag (min)	Discharge (L/min/ha)	Lag (min)	Discharge (L/min/ha)	Lag (min)	Discharge (L/min/ha)
1	02/20/86	850	1577	106	1675	69.4	55	61.0	*	*
2	03/13/86	1000	1084	63.5	660	55.6	-600	44.0	*	*
3	03/15/86	1645	1767	67.0	2145	62.5	1920	41.0	*	*
4	12/19/86	1330	828	7.0	587	5.4	499	4.5	765	6.2
5	01/01/87	1320	1812	12.7	1096	9.3	1262	9.5	1437	11.5
6	01/04/87	340	1690	30.2	1442	22.6	1438	20.1	1407	22.8
7	01/25/87	1210	1313	19.1	214	13.8	268	13.0	22	14.1
8	01/28/87	800	3315	42.3	1777	23.5	1563	21.9	1686	23.3
9	02/02/87	1420	2287	50.5	2283	27.4	2150	23.1	2387	27.6
10	02/14/87	2345	2761	42.3	813	26.7	281	20.5	678	26.3
11	03/03/87	55	++	++	622	6.7	1523	9.9	1040	10.5
12	03/05/87	1035	2176	45.9	3115	27.9	2338	23.6	2672	26.4
13	03/14/87	1550	2094	56.5	2391	39.6	1812	33.7	*	*
14	03/21/87	255	1611	24.7	213	9.3	1908	15.4	1324	17.0
15	11/20/87	1205	128	3.5	336	3.3	*	*	31	2.4
16	11/30/87	725	830	7.0	182	2.8	550	3.6	603	5.3
17	12/04/87	1135	++	++	++	++	1479	35.1	1582	38.2
18	12/06/87	900	1316	52.9	1650	55.6	1688	24.8	1967	27.0
19	12/10/87	755	1802	67.0	1954	71.8	2148	46.6	2251	50.0
20	01/04/88	625	2652	31.8	2980	28.0	2264	22.8	2983	25.3
21	01/11/88	150	1853	60.2	2423	49.5	1563	43.6	3125	52.8
22	01/16/88	850	2510	49.4	2304	41.5	1994	33.5	1917	65.4

Note: An '*' Denotes Missing or Questionable Data Not Used in Analysis; '++' Indicates Data Not Measured Since End Occurred After Start of Next Event

Table 4. Duration Data for Storm Events, Including Time from Start of Rainfall to Rainfall Median and End of Rainfall, and Time from Start of Runoff to Maximum Peak Discharge and End of Runoff at Study Sites.

	Start of Storm to Middle of Storm					Start of Storm to End of Storm				
Storm Number	Rain-fall (min)	MUN (min)	M1 (min)	K1 (min)	K2 (min)	Rain-fall (min)	MUN (min)	M1 (min)	K1 (min)	K2 (min)
1	--	--	*	*	*	9480	10727	10845	9360	*
2	--	--	*	*	*	9250	9944	9450	7965	*
3	895	1010	1200	765	*	1365	2642	2775	2430	*
4	140	242	80	100	400	315	1029	757	649	975
5	290	280	300	300	400	625	2292	1446	1542	1797
6	550	*	1810	1690	1760	1835	3208	2992	2828	2807
7	420	340	580	350	490	2435	3345	2384	2208	2942
8	155	760	1360	910	950	1025	4205	2647	2193	2556
9	285	280	1090	580	1010	1000	3037	3193	2870	3167
10	670	532	580	570	630	3820	6148	4108	3536	3993
11	240	600	460	1140	510	515	++	917	1618	965
12	505	800	1120	790	750	1070	2901	3820	3013	3377
13	990	680	1080	800	*	4150	5714	6061	5482	*
14	255	10	190	1450	480	475	1626	368	1963	1079
15	85	20	290	*	310	350	403	541	*	356
16	260	280	*	90	130	380	1015	347	535	778
17	2075	4650	4420	4610	4580	5180	++	++	6214	6327
18	155	180	790	450	430	395	1536	1910	1908	2277
19	2290	3100	3540	3180	*	3470	4957	5259	5353	5386
20	2225	1150	1490	910	670	3050	4187	4305	3379	3978
21	1665	2280	3590	*	*	3660	4363	5503	4383	5975
22	305	300	1150	670	960	2375	4640	4494	4074	4087

Note: An '*' Denotes Missing or Questionable Data Not Used in Analysis; '—' Indicates Data Not Measured Since All Corresponding Pipe Data was Missing; '++' Indicates Data Not Measured Since End Occurred After Start of Next Event

Table 5. Cumulative Rainfall from Start of Storm to Rainfall Median and End of Storm, and Cumulative Quickflow Runoff from Start of Runoff to Maximum Peak Discharge and End of Runoff at Study Sites.

		Start of Storm to Middle of Storm					Start of Storm to End of Storm			
Rain- Storm Number	fall (mm)	mum (mm)	M1 (mm)	K1 (mm)	Rain K2 (mm)	fall (mm)	NUN (mm)	M1 (mm)	K1 (mm)	K2 (mm)
1	--	--	*	*	*	--	--	*	*	*
2	--	--	*	*	*	194.1	86.11	63.40	35.60	*
3	24.4	4.49	6.00	2.20	*	48.8	12.51	10.50	7.20	*
4	13.2	0.26	0.03	0.02	0.20	26.4	0.87	0.38	0.20	0.47
5	19.9	0.94	0.38	0.45	0.56	39.9	5.39	1.41	2.0b	2.46
b	27.9	*	2.49	3.52	4.46	55.9	11.25	4.07	5.22	6.55
7	26.5	1.31	0.49	0.50	0.73	53.1	7.51	2.0b	3.38	3.00
8	16.0	1.70	1.12	1.34	1.11	32.0	6.22	2.19	3.42	3.70
9	25.7	1.63	3.79	2.05	5.72	51.4	15.10	12.61	9.87	14.02
10	36.8	4.89	1.52	3.11	3.29	73.7	29.57	15.09	14.93	17.99
11	19.5	1.08	0.05	0.30	0.11	38.8	++	0.11	0.35	0.20
12	29.7	8.24	5.08	4.67	3.95	59.4	22.58	17.57	14.61	16.42
13	44.9	6.20	4.68	3.13	*	89.9	33.42	30.04	19.79	*
14	9.5	0.007	0.01	0.34	0.12	19.1	1.32	0.02	0.45	0.23
15	17.4	0.006	0.04	*	0.01	34.8	0.11	0.07	*	0.01
1b	24.2	0.48	*	0.04	0.02	48.5	1.45	0.27	0.19	0.38
17	99.9	35.22	20.36	17.02	21.97	199.9	++	++	29.59	43.23
18	15.6	1.70	1.99	1.87	2.02	31.2	7.84	5.20	7.87	11.51
19	47.5	20.55	18.51	13.99	*	95.0	40.38	40.86	27.05	39.30
20	29.0	5.57	3.83	1.86	0.94	58.0	27.48	14.96	11.23	11.85
21	26.4	9.78	14.06	*	*	52.8	17.26	21.59	*	31.19
22	24.7	1.65	3.03	2.00	4.31	49.3	20.81	13.59	10.48	16.03

Note: An ‘*’Denotes Missing or Questionable Data Not Used in Analysis; ‘--‘ Indicates Data Not Measured Since All Corresponding Pipe Transact Data Missing; ‘++’ Indicates Data Not Measured Since End Occurred After Start of Next Event

Timing Comparisons

The calculation of variables for timing parameters used Data Treatment 1. Results of t-tests for individual comparisons, and significance determinations for this parameter category are listed in Table 6. Variable mean and standard deviation values are also reported in Table 6. No significant difference was detected for any of the transects compared to MUN for time at start of runoff. For time at maximum peak discharge, all three sites demonstrated a significant difference in comparison to the stream channel. Time at end of runoff was; significantly different for K1 compared to MUN, but no significant difference was detected for the other two sites in comparison to MUN.

Duration Comparisons

Hypotheses tests for duration parameters were also based on variables created by Data Treatment 1. The results obtained for the two parameters in this category are given in Table 7. Variable mean and standard deviation values are also reported in Table 7.

Results indicate a significant difference between M1 and MUN for time from start of runoff to maximum peak discharge. K1 and K2 comparisons with MUN did not demonstrate a significant difference with regard to this parameter.

The second duration parameter was time from start of runoff to end of runoff. This also resulted in one determination of no

Table 6. Results of T-tests for Timing Parameters at Pipe Transects M1, K1, and K2 Compared to Stream Channel MUN.

Paired Comparison		Time at Start of Runoff		Time at Maximum Peak Discharge		Time at End of Runoff
M1 | MUN	t=	- 0.29	t=	4. 54	t=	- 1.52
	n=	22	n=	18	n=	20
	p=	0.77	p=	0.0000*	p=	0.15
	x=	- 10.5	x=	319	x=	- 258
	sd=	169	sd=	298	sd=	761
K1 | MUN		2.32		2.88		- 2.91
		21		17		19
		0.031		0.011		0.0093
		86.6		250		- 536
		171		358		801
K2 | MUN		1.02		3.26		- 1.05
		18		15		16
		0.32		0.0057		0.31
		45.2		223		- 227
		188		265.		863

Note: t = t-test value obtained for paired comparison
n = sample size of paired comparison
p = probability (significance is at the 0.05/3=0.0167 level)
x = mean for paired comparison (minutes)
sd = standard deviation for paired comparison (minutes)
'*' = significance probability less than 0.00005

Table 7. Results of T-tests for Duration Parameters at Pipe M1, K1, and K2 Compared to Stream Channel MUN

Paired Comparison		Time from Start of Runoff to Maximum Storm Discharge		Time from Start of Runoff to End of Storm Runoff
M1 | MUN	t=	3.65	t=	- 1.32
	n=	18	n=	20
	p=	0.0020	p=	0.20
	x=	339	x=	- 236
	sd=	394	sd=	799
K1 | MUN		1.51		- 3.18
		17		19
		0.15		0.0052
		145		- 623
		397		855
K2 | MUN		1.88		- 1.16
		15		16
		0.081		0.26
		152		- 266
		312		917

Note: t= t-test value obtained for paired comparison
n= sample size of paired comparison
p= probability (significance is at the 0.05/3=0.0167 level)
x= mean for paired comparison (minutes)
sd= standard deviation for paired comparison (minutes)

significant difference, but in this case the significance pertained to K1 in ,comparison to MUN.

Discharge Comparisons

The results obtained from hypotheses tests for this category of parameters are reported in Table 8. Variable mean and standard deviation values are also reported in Table 8. Comparison tests for this group used, the variable created by Data Treatment 2. All but one comparison in this entire group demonstrated a highly significant difference for pipe relative to MUN. The exception was the comparison of K2 and MUN for the log-transformation of discharge at the start of runoff.

Runoff Comparisons

The hypotheses for the two runoff parameters utilized Data Treatment 2 to construct variables for testing. Results for these tests are displayed in Table 9. Variable mean and standard deviation values are also reported in Table 9. None of the three pipe tested as significantly different than MUN in terms of the log-transformed values ,for cumulative unit-area runoff from start of storm to maximum peak discharge. The results were exactly opposite for comparisons pertaining to log-transformed unit-area runoff values from star to end of events. All comparisons indicated a highly significant difference in this regard.

Table 8. Results of T-tests for Discharge Parameters at Pipe M1, K1, and K2 Compared to Stream Channel MUN

Paired Comparison		Discharge at Start of Runoff	Maximum Peak Discharge	Discharge at End of Runoff
M1 | MUN	t=	- 3.32	- 6.35	- 5.25
	n=	22	18	20
	p=	0.0032	0.0010	0.0010
	z=	- 0.68	- 0.67	- 0.33
	sd=	0.96	0.45	0.28
K1 | MUN		- 4.81	- 9.78	-13.85
		21	17	19
		0.0000*	0.0010	0.0010
		- 0.93	- 0.68	- 0.50
		0.89	0.28	0.16
K2 | MUN		- 1.95	- 7.01	- 5.38
		18	15	16
		0.068	0.0010	0.0010
		- 0.46	- 0.57	- 0.32
		0.99	0.32	0.24

Note: t= t-test value obtained for paired comparison
n= sample size of paired comparison
p= probability (significance is at the 0.05/3 = 0.0167 level)
z= mean for paired comparison (natural-log of L/min/ha)
sd= standard deviation for paired comparison (natural-log of L/min/ha)
'*'= significance probability less than 0.00005

Table 9. Results of T-tests for Runoff Parameters at Pipe M1, K1, and K2 Compared to Stream Channel MUN

<table>
<tr><th>Paired Comparison</th><th>Cumulative Unit-area Runoff From Start of Storm to Maximum Storm Discharge</th><th>Cumulative Unit-area Runoff from Start of Storm to End of Storm</th></tr>
<tr><td>M1 | MUN</td><td>t= - 1.37</td><td>t= - 3.49</td></tr>
<tr><td></td><td>n= 19</td><td>n= 19</td></tr>
<tr><td></td><td>p= 0.19</td><td>p= 0.0026</td></tr>
<tr><td></td><td>x= - 0.35</td><td>x= - 0.78</td></tr>
<tr><td></td><td>sd= 1.1</td><td>sd= 0.97</td></tr>
<tr><td>K1 | MUN</td><td>- 1.54</td><td>- 6.98</td></tr>
<tr><td></td><td>18</td><td>17</td></tr>
<tr><td></td><td>0.14</td><td>0.0000*</td></tr>
<tr><td></td><td>- 0.49</td><td>- 0.78</td></tr>
<tr><td></td><td>1.3</td><td>0.46</td></tr>
<tr><td></td><td>1.4</td><td></td></tr>
<tr><td>K2 | MUN</td><td>- 0.88</td><td>- 3.29</td></tr>
<tr><td></td><td>16</td><td>16</td></tr>
<tr><td></td><td>0.39</td><td>0.0049</td></tr>
<tr><td></td><td>- 0.31</td><td>- 0.62</td></tr>
<tr><td></td><td>1.4</td><td>0.75</td></tr>
</table>

Note: t= t-test value obtained for paired comparison
n= sample size of paired comparison
p= probability (significance is at the 0.05/3 = 0.0167 level)
x= mean for paired comparison (natural-log of mm)
sd= standard deviation for paired comparison (natural-log of mm)
'*'= significance probability less than 0.00005

DISCUSSION

Storm Conditions

The events examined in this study represent a diverse sample of precipitation events. This is evidenced by rainfall data reported in Tables 4 and 5. Total storm rainfall ranged from approximately 19 to 280 mm (mean = 64.4 mm), with duration ranging from approximately 5 to 160 hrs (mean = 42.6 hr). The average rainfall intensity for,these events ranged from 0.87 to 7.6 mm/hr (mean of average intensities = 2.8 mm/hr).- Storm duration prior to time of median rainfall ranged from approximately 13 to 73 percent of total storm length (mean = 40.3 percent); Average rainfall intensity prior to median rainfall ranged from 0.78 to 12 mm/hr (mean = 4.0 mm/hr).

This diversity contributed to a highly variable runoff response at the-study sites. Similar amounts of rainfall, distributed dissimilarly during different events, can result in hydrograph forms that are either single-peaked (Storm 9) or multi-peaked (Storm 21). Rainfall timing influence on hydrograph form was also apparent for Storms 10 and 19. These storms were of similar length and generally comparable for total rainfall amount, and produced comparable amounts of runoff. However, the timing of rainfall delivery was different, causing An early and flashy peak for storm 10, and a much later, but similarly flashy peak for storm 19.

Even where rainfall characteristics were similar during different events, the magnitude of runoff response was strongly influenced by antecedent conditions. For example, Storms 4 and 18 were similar in terms of length and amount of rainfall, but storm 18 occurred during wetter conditions and resulted in substantially more runoff at all sites.

Timing

Study results suggested a general similarity between pipe transects and MUN for time at start of runoff. An examination of the data supports this finding, at least for certain types of storm conditions. A similar lag was observed for four storms where antecedent conditions were relatively dry and initial rainfall was relatively intense (Storms 8, 9, 15, 16). In these cases, transect runoff was measured to precede MUN, or lag MUN by no more than one hour, for at least two transects. For one storm event, all transects may, have preceded MUN in runoff response. This storm (Storm 21) was characterized by less-intense initial rainfall and relatively-wet antecedent conditions. Although all three transects were measured as preceding MUN for storm 21, the terminology "may have" is used because of two data quality issues discussed below.

Contrary to these cases, all pipe-transects were observed to greatly lag MUN for one storm where antecedent conditions were relatively-dry and initial rainfall intensities were exeptionally low (Storm 20).

In some cases, the similarity demonstrated between pipe transects and MUN for time at start of runoff may be affected by a reconstruction applied to MUN data for some storms. The reason and method used for this reconstruction is described in METHODS. Reconstruction was primarily intended to provide a better estimate of discharge at start of runoff. Reconstructed times-are simply 10 minutes earlier than the first conclusive evidence of runoff at MUN. MUN data used in the analysis overestimates MUN lag time in at least some cases; whether the resulting bias is typically on the order of minutes or hours is not known. Similar timing was indicated for some of the stormy where MUN data was not reconstructed (storms 1, 12, 13, 14). For each of these events, data for at least two transects indicated an earlier response than for MUN, or lagged MUN by no more than one hour. Moderate to wet antecedent conditions were associated with each of these events.

All pipe transects tested as significantly different than MUN, for time of maximum peak. In fact, transects lagged MUN with regard to time of maximum peak discharge for 44 of the 50 individual comparisons. Mean lag-time differences for this parameter, reported in Table 6, ranged from 223 to 319 minutes. Standard deviations obtained for these comparisons (Table 6) were relatively large, ranging ,from 265 to 358 minutes. The large standard deviations may. reflect general errors associated with data collection during storm events (see METHODS). It may also reflect local differences in rainfall intensity during storm events, or differences among swales with regard to pipe network morphology.

Four of 13 events having time-at-maximum-peak data for all study sites indicated a consistent peak time among transects relative to MUN (Storms 5, 7, 10, 17): For each of these cases, characterized by peaks that resulted from very concentrated periods of rainfall, all transects peaked within 100 minutes of each other. For storms associated with dry to moderate wetness conditions, the three transects lagged Mi1rT peak by an average of 103 minutes for Storm 5, 120 minutes for Storm 7, and 160 minutes for storm 10. Storm 17 was a complex event with a late-event maximum peak. For this storm, representing very wet conditions, the average lag time at the transects preceded MUN peak by 33 minutes.

Although time at end of runoff events tested as not significantly different far two of the transects compared to MUN, relatively large standard deviations were obtained (Table 6). To some extent, these differences reflect a weakness of the study methodology for determining end times. End of runoff times were determined by application of the H-H line to storm hydrographs. Differing sensitivity among study sites to late-event rainfall may have influenced determination of this parameters values in some cases.

End of runoff at transects was often substantially earlier than at MUN. Storms 7, 8, and 10 all indicated a large difference in this respect. Each of these storms evidenced concentrated rainfall early in the event. and greatly reduced amount and intensity of rainfall near the end of events. In these cases, MUN appeared more responsive than transects to late-event rainfall.

Contrary to these events, Storms 12, 18, 19 had a much larger concentration of rainfall near the end of events. For these storms, which had end-of-storm data for all study sites, runoff at all three transects lasted longer than at MUN.

Results for each of the two duration parameters indicated no significant difference for two transects relative to MUN. A different transect pair was indicated for each parameter. The suggestions,of general similarity are of limited usefulness due to relatively high standard deviations (Table 7). An examination of the mean differences does suggest that all transects are more likely to have longer duration to peak than MUN, but that MUN is more likely to have longer duration to end of runoff than all transects. Dotplots for the duration-to-peak variable (Figure 7) suggest that, on average, transect M1 takes longer to peak than all other sites.

Discharge and Runoff

Test results indicate significant differences for two of the three transects with regard to MUN for log-transformed unit-area discharge at start of runoff. Results for the K2 comparison, indicated as not significantly different, were partially influenced by data reported for Storm 22. This data pair, which suggested that K2 had almost twice the starting discharge as MUN, may have been in error. Data for K2 during this period was affected by an over-measurement issue discussed in METHODS. Reconstruction may not have adequately corrected this error.

Typically, much more discharge was measured at MUN compared to all transects at the onset of events. This is intuitively reasonable. MUN receives baseflow contributions from an area much larger than the study swales. The notable aspect of this difference is that it also appears to apply to wetter conditions, represented by cases where successive storms were closely spaced. This interpretation may also be influenced by reconstruction of MUN data for start of storm.

Reconstructed data used the last discharge measured prior to data-record time gaps. These measurements were collected 2.5 to 24 hours (mean = 10 hours) prior to the times ultimately used as start of storm runoff. Discharge was declining during each time gap, therefore the values used in the study were overestimates of actual discharge at MUN. An examination of time gaps, and their associated rates of decline, would allow a more accurate determination of MUN discharge at start of runoff. It is unlikely that this would change the basic findings of significant difference, since large differences were observed in most cases.

The significant differences measured for all transects relative to MUN for maximum peak unit-area discharge were based on log-transformed data (Data Treatment 2). Contributing area for transect discharge was assumed to be the same as contributing area measured for the surface swales containing the pipe transects. On this basis, MUN unit-area discharge was larger than transect discharge in every ease. Although Data Treatment 2 was used to construct the variable for testing, dotplots for the variable constructed by Data Treatment 3 demonstrated a similar distribution. In fact, these two data treatments are similar: Data Treatment 2 is a log-transformation of the algorithm used to construct Data Treatment 3. The use of Data Treatment 3 would not have changed hypotheses results, but does provide a more interesting perspective on the differences observed between pipe transects and MUN.

For Data Treatment 3, mean and median ratios were similar for each variable. The standard deviations were moderately large, but the consistency of results among transects was good. The mean ratio and standard deviation obtained for each variable was: 0.56 and 0.21 l/min/ha for M1, 0.53 and 0.13 l/min/ha for K1, and 0.59 and 0.18 l/min/ha for K2, where each transect was compared to MUN. The consistency implied by these results warrants further examination as part of another study. In particular, it is possible that a simple, physically-based model could serve to interpret differences between pipe transect and MUN peak discharge.

The comparisons of log-transformed unit-area runoff from start of runoff to maximum peak discharge indicated no significant difference between any of the pipe transects and MUN. However, interpretation of this parameter is problematic. As indicated in the discussion for time at maximum peak discharge, transect peaks generally lag MUN peak by more than 200 minutes. Study data indicate that substantial rainfall sometimes follows MUN peak but precedes transect peak. This occurs, for example, during Storms 18 and 20. In these cases, parameter values are comparing runoff for different periods of time associated with different amounts of rainfall. Therefore, study results for this parameter can not be construed as indicating a strong similarity between transects and MUN.

Results indicated significant differences for all pipe transect and MUN comparsions for log-transformed unit-area discharge at end of runoff. To some extent, these differences are due to the use of the H-H line for determining time and discharge at end of runoff. As previously discussed for ending time, ending discharge determination can be influenced by different sensitivity among sites to late-event precipitation. This parameter used Data Treatment 2, but once again, Data Treatment 3 provides a more interesting perspective for comparisons.

Data Treatment 3 produces variables having similar mean and median ratios, and standard deviations were moderately large. Two of the three transects showed consistency with respect this parameter. The respective mean ratio and standard deviation obtained for each transect compared to MUN was: 0.74 and 0.19 for M1, 0.62 and 0.09 for K1, and for K2, 0.74 and 0.20. Combined with the interpretation for maximum peak discharge, this information may be useful for additional study. If peak discharge at transects can be successfully modeled, then transect recession rates from peak discharge to end of runoff may also follow a very predictable form in comparison to MUN.

For all pipe transects, total unit-area quickflow runoff comparisons indicated a significant difference relative to MUN regardless of data treatment selection. These comparisons also used log-transformed values. MUN had more total runoff in nearly all cases. Using Data Treatment 3 for this parameter would have resulted in similar mean and median ratios, though standard deviations were relatively high. In particular, mean ratio and standard deviation results for each transect compared to MUN were: 0.59 and 0.31 for M1, 0.50 and 0.20 for K1, and for K2, 0.68 and 0.45.

Evaluation of Study Objectives

The first study objective was to determine whether concentrated subsurface (pipe transect) discharge characteristics were measurably similar to surface channel discharge for the events observed. The test results indicate some very generalized similarities as well as significant differences.

The data demonstrate that pipes can capture and convey storm runoff at start of events as rapidly as the study surface channel, provided that certain storm conditions exist. Those conditions include: intense initial storm rainfall, even when combined with relatively-dry antecedent conditions; and less-intense initial rainfall combined with relatively-wet antecedent conditions. Pipe transect response at maximum storm peak, even under wetter conditions, is generally not as flashy as the surface channel response. The surface channel peaks earlier, and with larger magnitude than pipe transects. Pipe response is very dynamic under wet conditions, but once rainfall inputs cease, transect response falls off more quickly than for the surface channel. Consequently, runoff events at the surface channel generally last longer.

Flashier peaks and longer duration at the surface channel results in the finding that the surface channel transports more runoff during storm events. The form of pipe transect hydrographs, at least from the time of maximum peak to end of runoff, may have a predictable relationsip compared to the surface channel.

In summary, it appears that pipe transect runoff is probably somewhere between a surface channel response and a matrix throughflow response in terms of timing and magnitude characteristics. This is consistent with preliminary findings presented by Ziemer and Rice (1990), who examined peak response times for individual pipe, surface channel, and piezometer data at this same study area.

The interaction of antecedent conditions and rainfall intensity may be the most important influence determining whether pipe response is similar to surface channel response for timing. Two recent studies have also emphasized the importance of antecedent conditions and rainfall intensity, though neither study was comparing pipe and stream response characteristics.

Ziemer and Albright (1987) examined a subset of the data used in this study to determine that the magnitude of storm peaks and troughs for some individual pipes were correlated with antecedent precipitation conditions. Jones (1988) conducted a study of pipe runoff characteristics in Wales. Jones determined that initial rainfall intensity prior to pipe response was more important than antecedent conditions for determining the lag time at start of runoff.

The typically larger storm peaks observed for the surface channel may be an indication of the importance of saturation overland flow mechanisms in the study area. The definition of saturation overland flow precludes the possibility that these mechanisms contribute to pipe runoff, though they may be a component of channelized surface runoff. However, saturation overland flow was not identified during the storms measured during the study period.

It is probable that transect discharge is concentrated and routed from an area different in size than the surface swales that contain them. Given the limited number of pipes identified during transect excavation, it seems more likely that the true contributing area for measured pipe discharge is smaller, not larger, than the surface swales. If this is the case, unit-area based calculations of transect discharge and runoff reported in this study underestimate the actual efficiency of pipe networks for routing storm precipitation in the study setting.

The second objective was to determine if pipes were an important source of storm runoff from study swales. Here again, the test results do not provide a statistically-sound basis to address the objective. The calculated mean of transect runoff at the three study swales represented 50-68 percent as much runoff as was measured at the surface channel. The percentages observed here are comparable to the amount of surface channel discharge attributed to pipeflow by Jones and Crane (1984) and Wilson and Smart (1984) at their study sites in the United Kingdom. However, Tsukamoto et al. (1982) reported 100 percent runoff from swales; Swanson et al. (1989), nearly 70 percent in a 50-ha drainage.

In this study setting, it is considered unlikely that the larger watershed has as large a concentration of pipes as was evidenced in the study swales. Therefore, pipeflow contribution to channelized runoff is expected to be something less than 50 percent at this study site. How much less is not determinable at present.

The study results relied on consistent application of a single hydrograph separation technique. Other techniques would yield different results. However, the responsiveness of pipe discharge to rainfall inputs, and the volume of runoff measured, provide a reasonable basis to characterize pipe runoff-as an important source of runoff from the study swales. How important it is in comparison to runoff produced by subsurface matrix discharge is not known at present.

Recommendations

Several factors limited the usefulness of study results. The variety of storm conditions and variable nature of pipe response, combined with small sample sizes for comparisons, reduced the effectiveness of the comparisons for evaluating the strength of similarities and differences. In addition, a number of biases and random errors were carried in the data records. These problems acted to dilute the strength of study results.

A steeper rate-of-rise for the H-H line-would have created a larger sample size for comparisons by converting some single mutli-peaked events into separate events for analysis. Use of an alternative H-H line rate-of-rise should be done in a manner that emphasizes common rainfall inputs--and results in comparable hydrograph features--for all study sites.

The selection and definition of runoff characteristics for comparison should be reconsidered. For example, Jones (1988) identified amount and intensity of rainfall prior to runoff reponse as important determinants of lag time at start of runoff. Each of these might serve as useful parameters for comparisons at this study site. Unfortunately, Jones’ paper was not identified until all analysis for this study had been completed. Therefore, a parallel investigation, which would have provided useful information, was not possible.

The models (data treatments) used for comparison should be developed in a more rigorous fashion. For example, it might be useful to develop physically-based models for runoff characteristics--as suggested earlier in this study for maximum peak discharge--then use model results as a basis for comparisons. Rainfall intensity and an antecedent precipitation index, such as that used by Ziemer and Albright (1987), would be useful components to incorporate in models. Flowpath-length measurements or estimates, as used by Ziemer and Rice (1990) and Jones (1988) may also serve as useful model components. In some cases, models could be used to transform pipe discharge data for comparison with stream discharge, which is generally a more accurate estimate of total runoff. Where models are intended as a theoretical construct of subsurface flow dynamics, it may be more reasonable to directly test model output against measured pipe runoff characteristics. The hypotheses testing procedure used in this study could serve as a useful analysis tool for either approach.

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Appendix A. Stream Discharge, Pipe Transect Discharge, Cumulative Rainfall, and Rainfall Intensity Data for Storms 1-3.

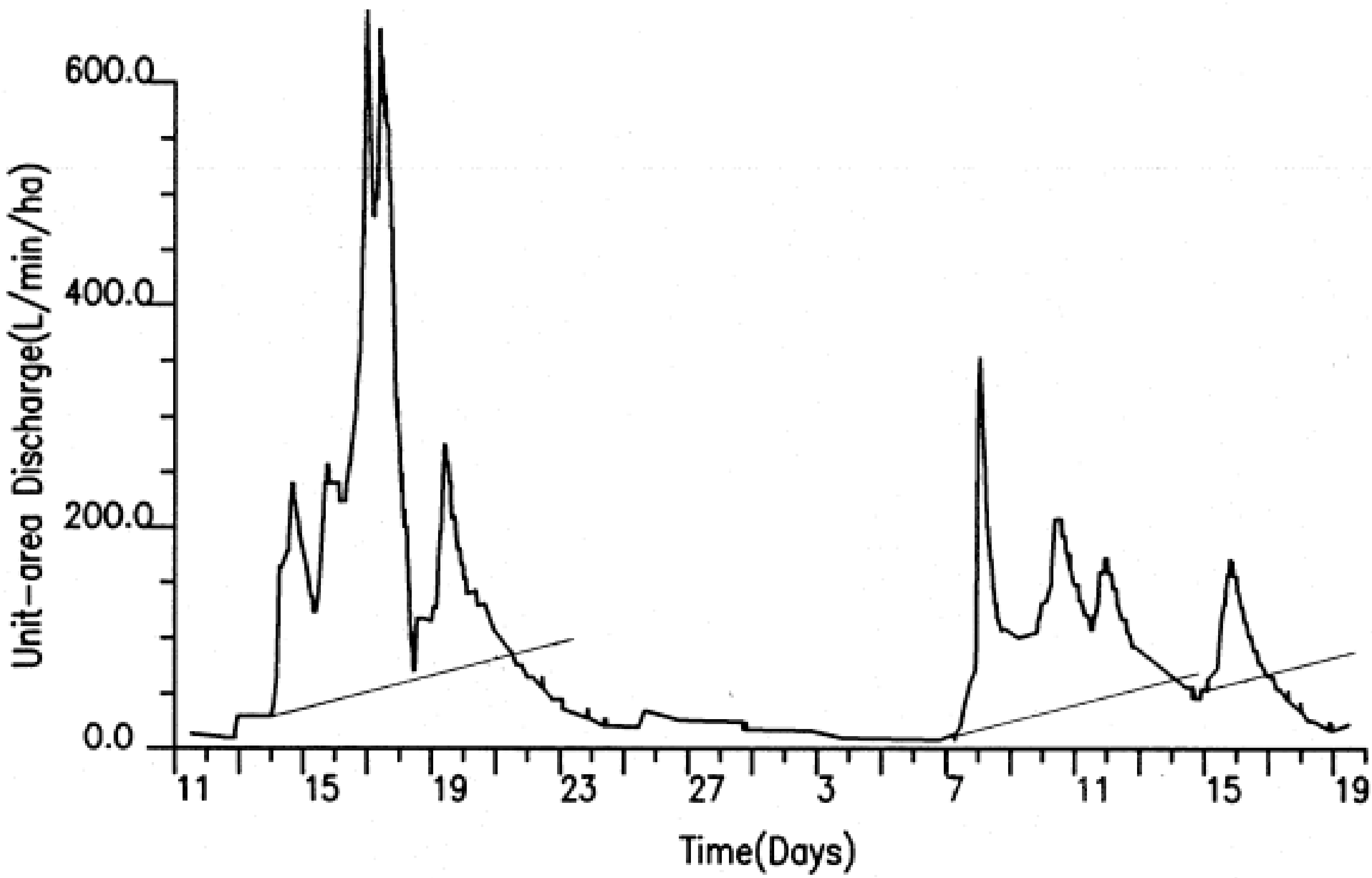


Figure A-6. Discharge at Stream Site Mun for Storms 1-3, Covering Period 02/11/86 to 03/20/86.

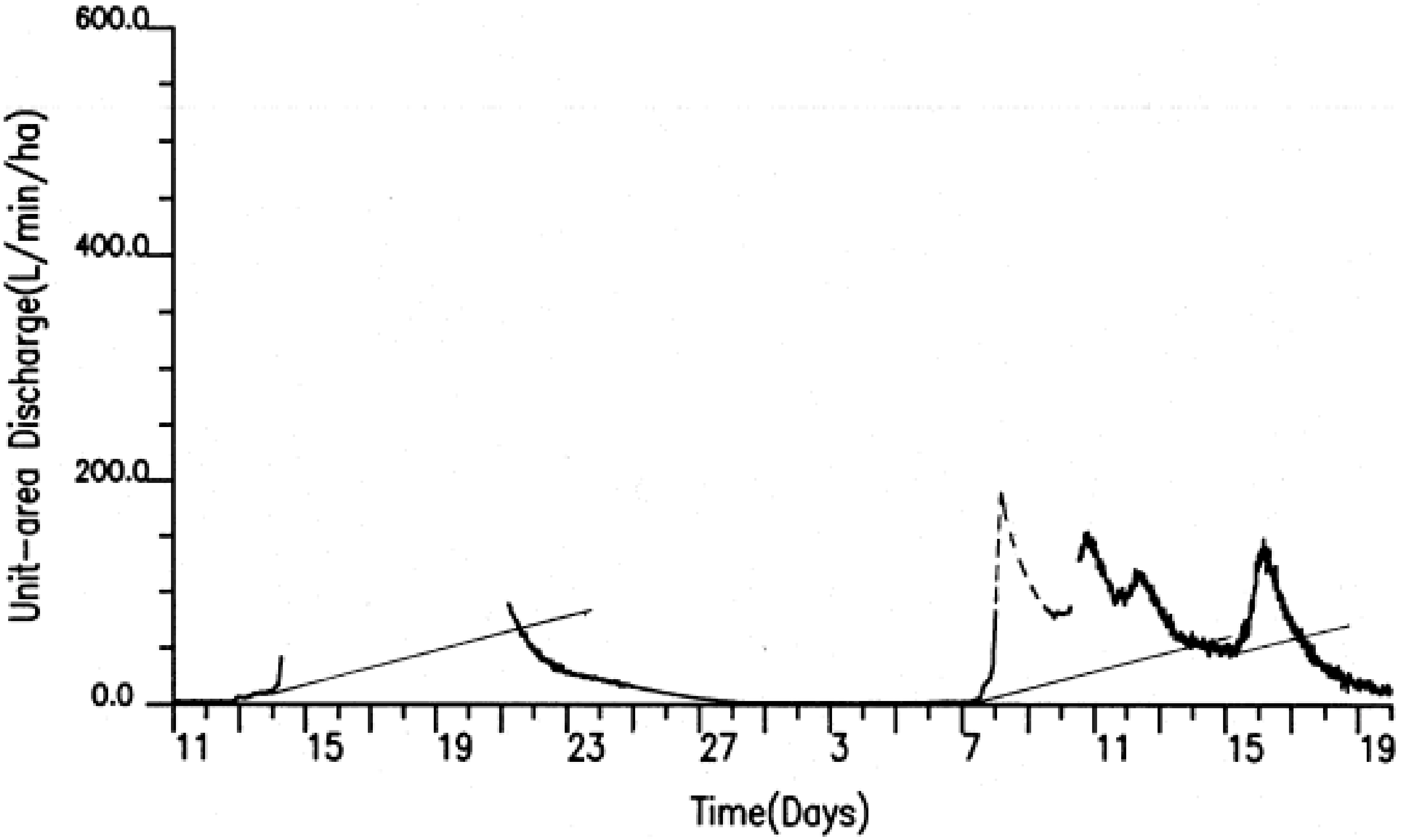


Figure A-7. Discharge at Piping Site M1 for Storms 1-3, Covering Period 02/11/86 to 03/20/86.

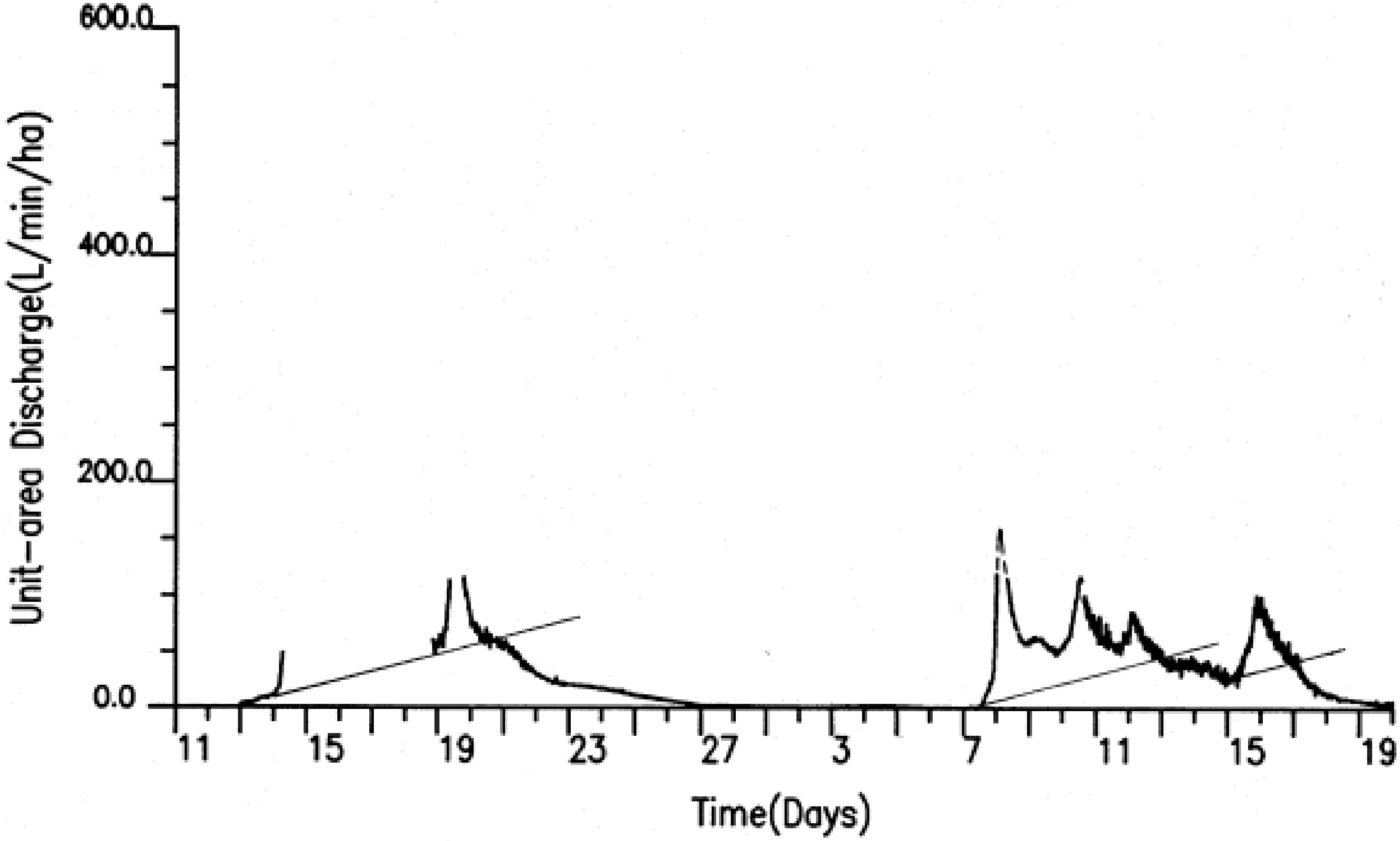


Figure A-8. Discharge at Piping Site K1 for Storms 1-3, Covering Period 02/11/86 to 03/20/86.

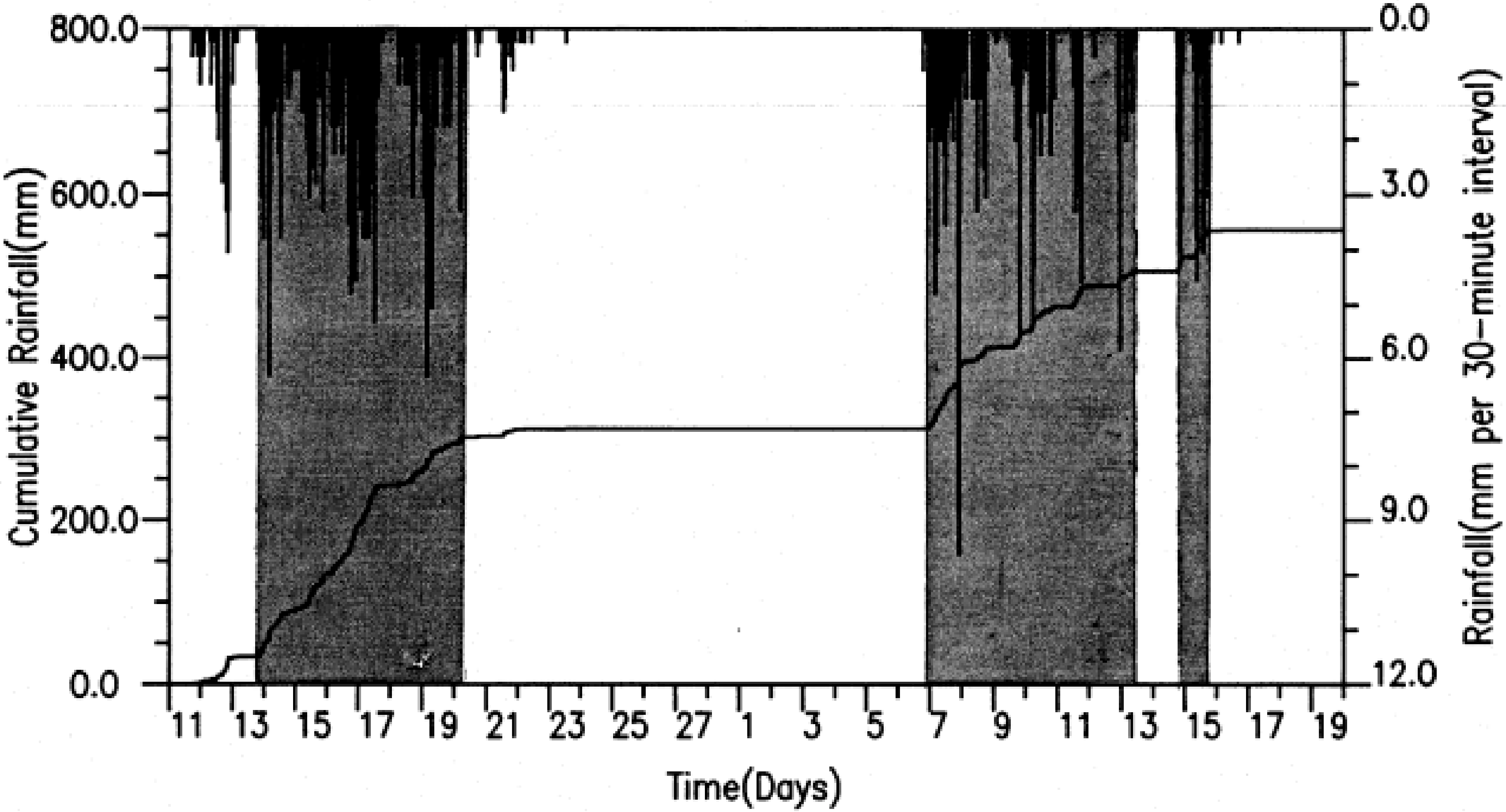


Figure A-9. Cumulative Rainfall and Rainfall Intensity for Storms 1-3, Covering Period 02/11/86 to 03/20/86.

Appendix B. Stream Discharge, Pipe Transect Discharge, Cumulative Rainfall, and Rainfall Intensity Data for Storms 4-6.

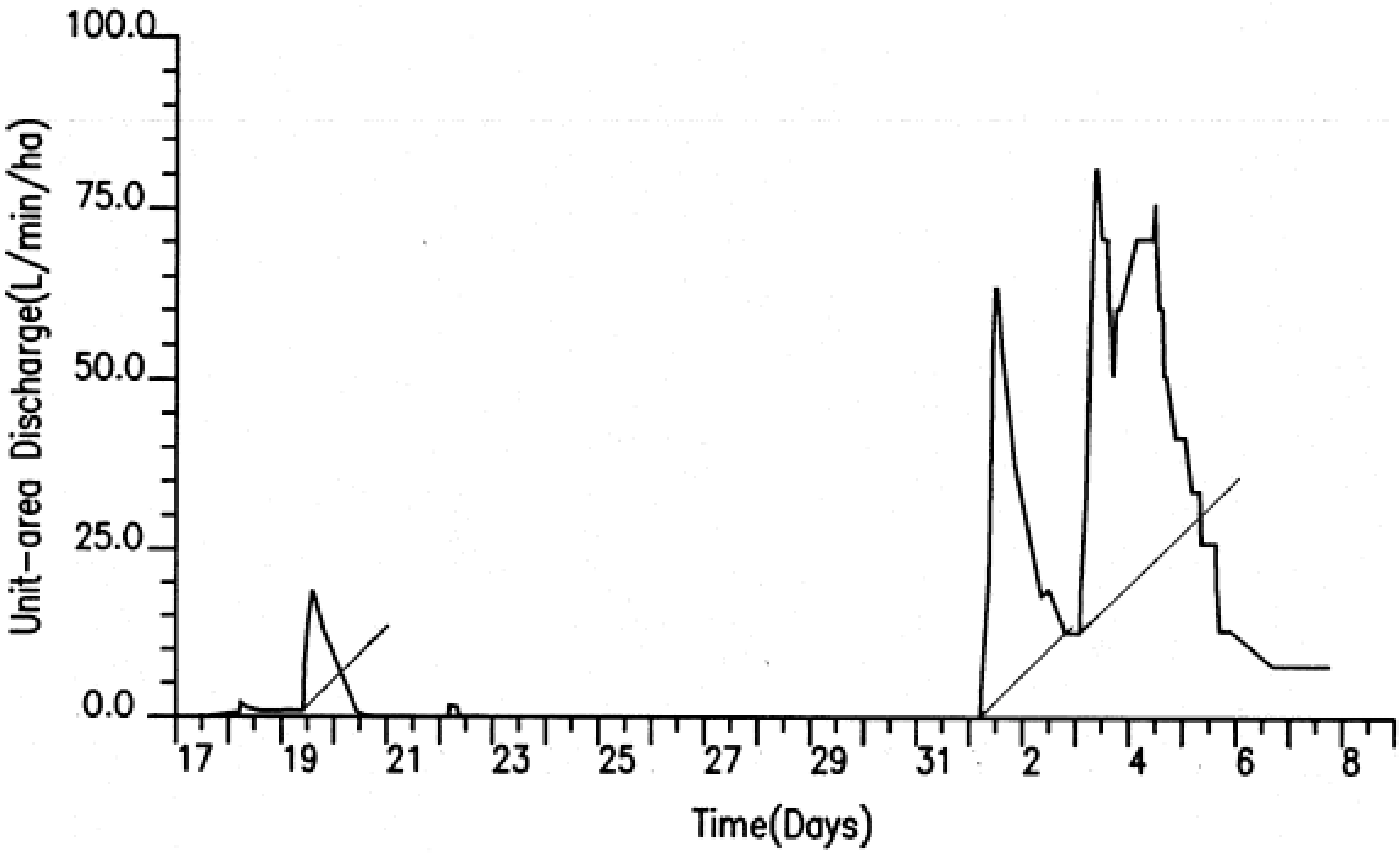


Figure B-10. Discharge at Stream Site MUN for Storms 4-6, Covering Period 12/17/86 to 01/09/87.

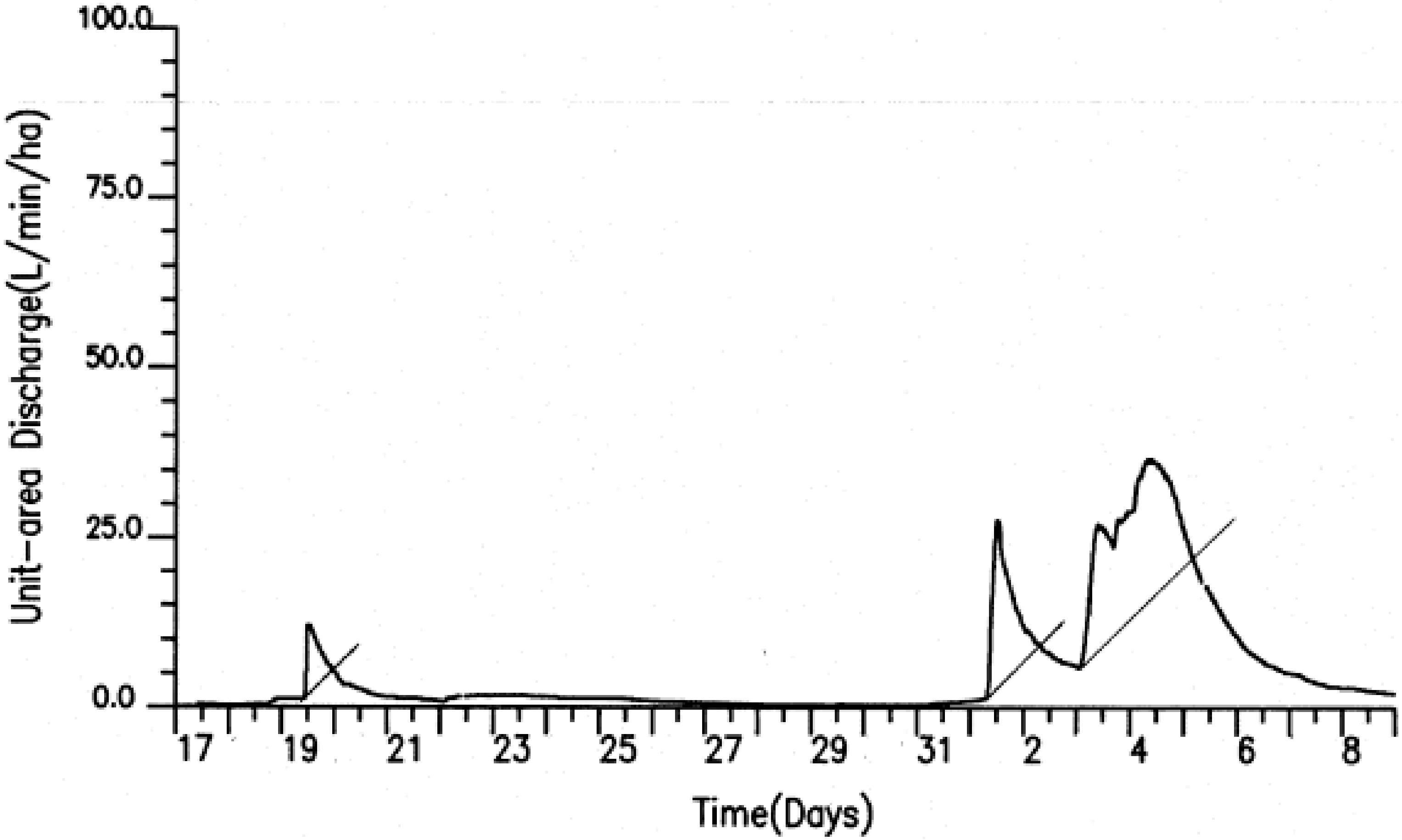


Figure B-11. **Discharge at Piping Site M1 for Storms 4-6, Covering Period 12/17/86 to 01/09/87.**

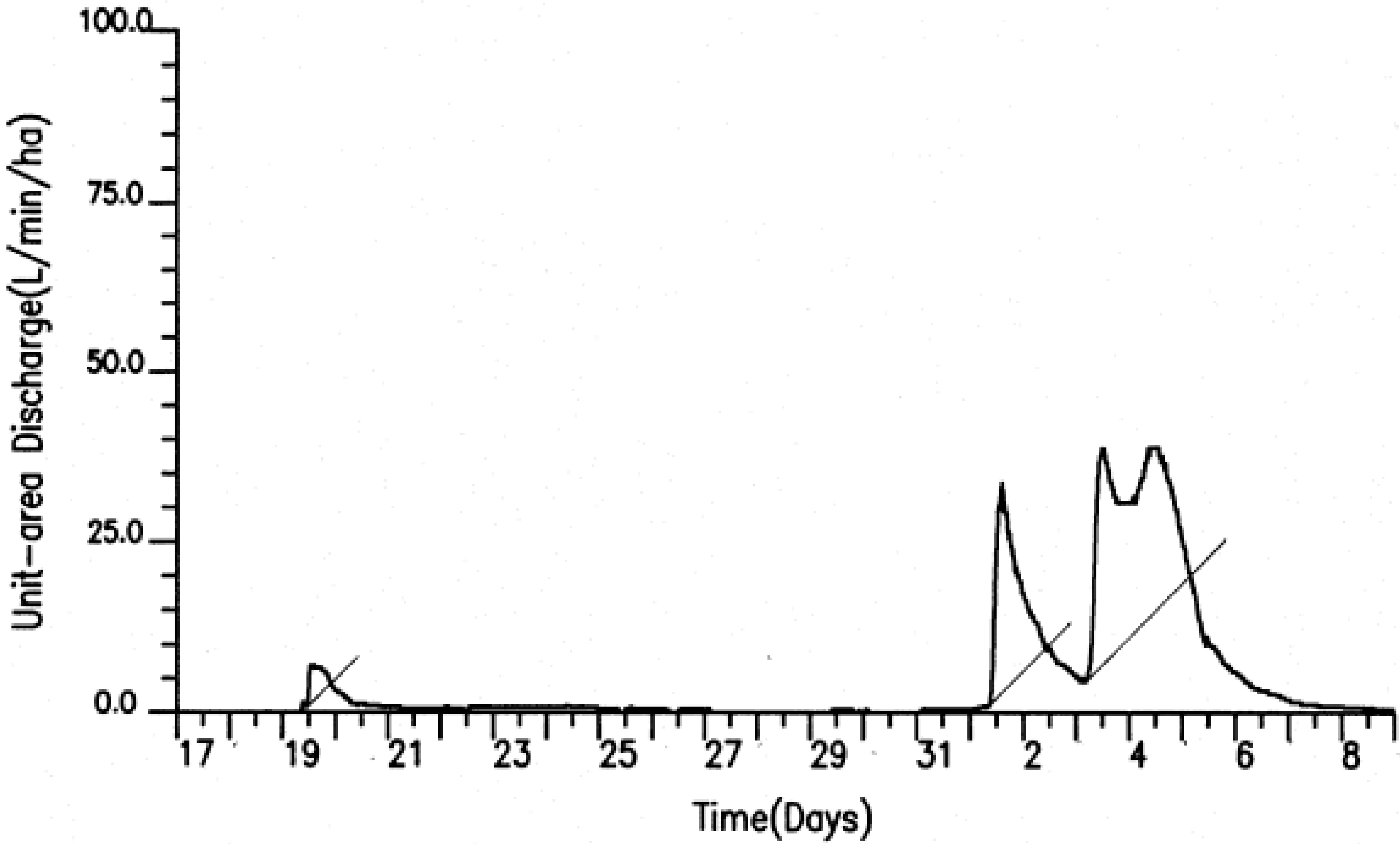


Figure B-12. Discharge at Piping Site K1 for Storms 4-6, Covering Period 12/17/86 to 01/09/87.

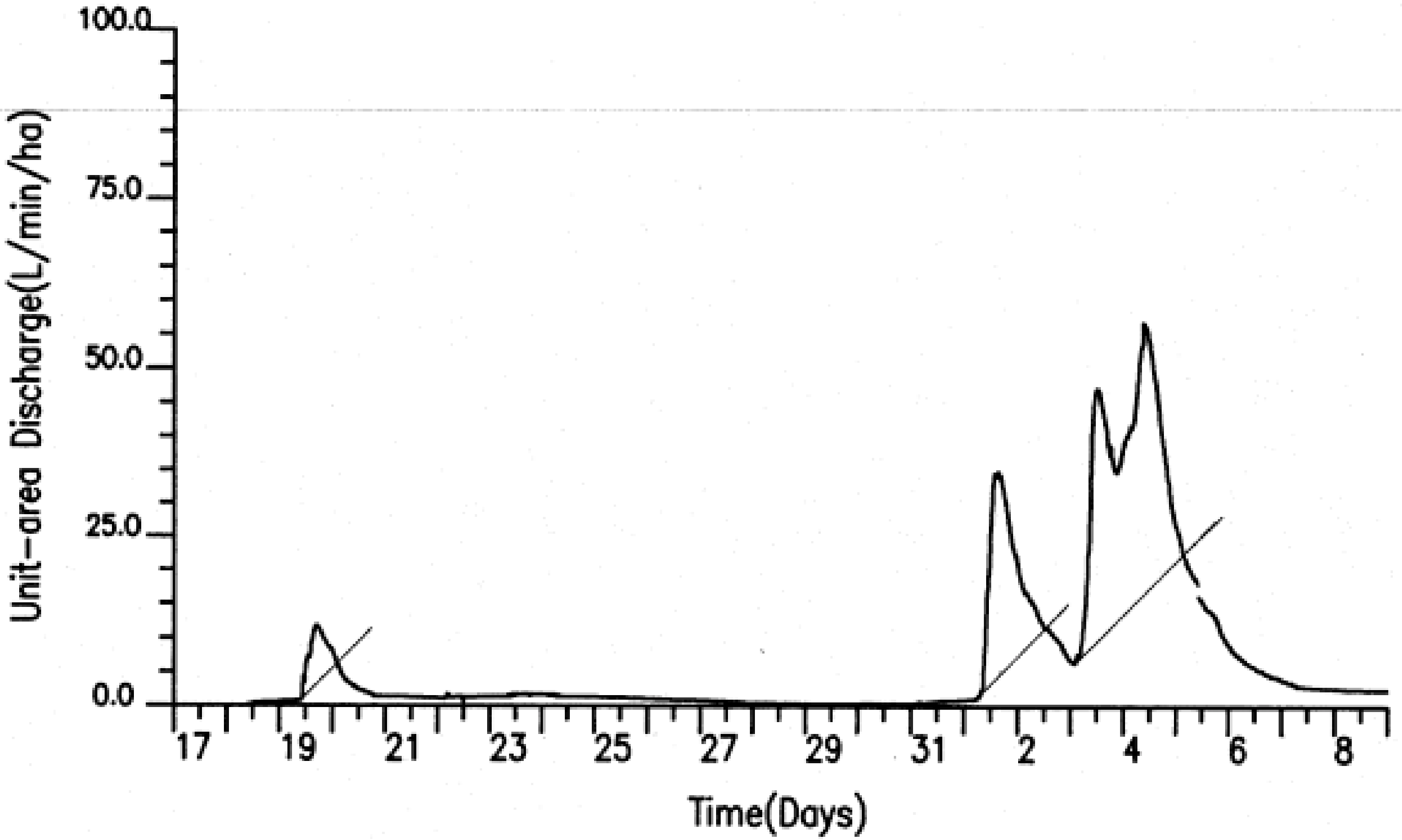


Figure B-13. Discharge at Piping Site K2 for Storms 4-6, Covering Period 12/17/86 to 01/09/87.

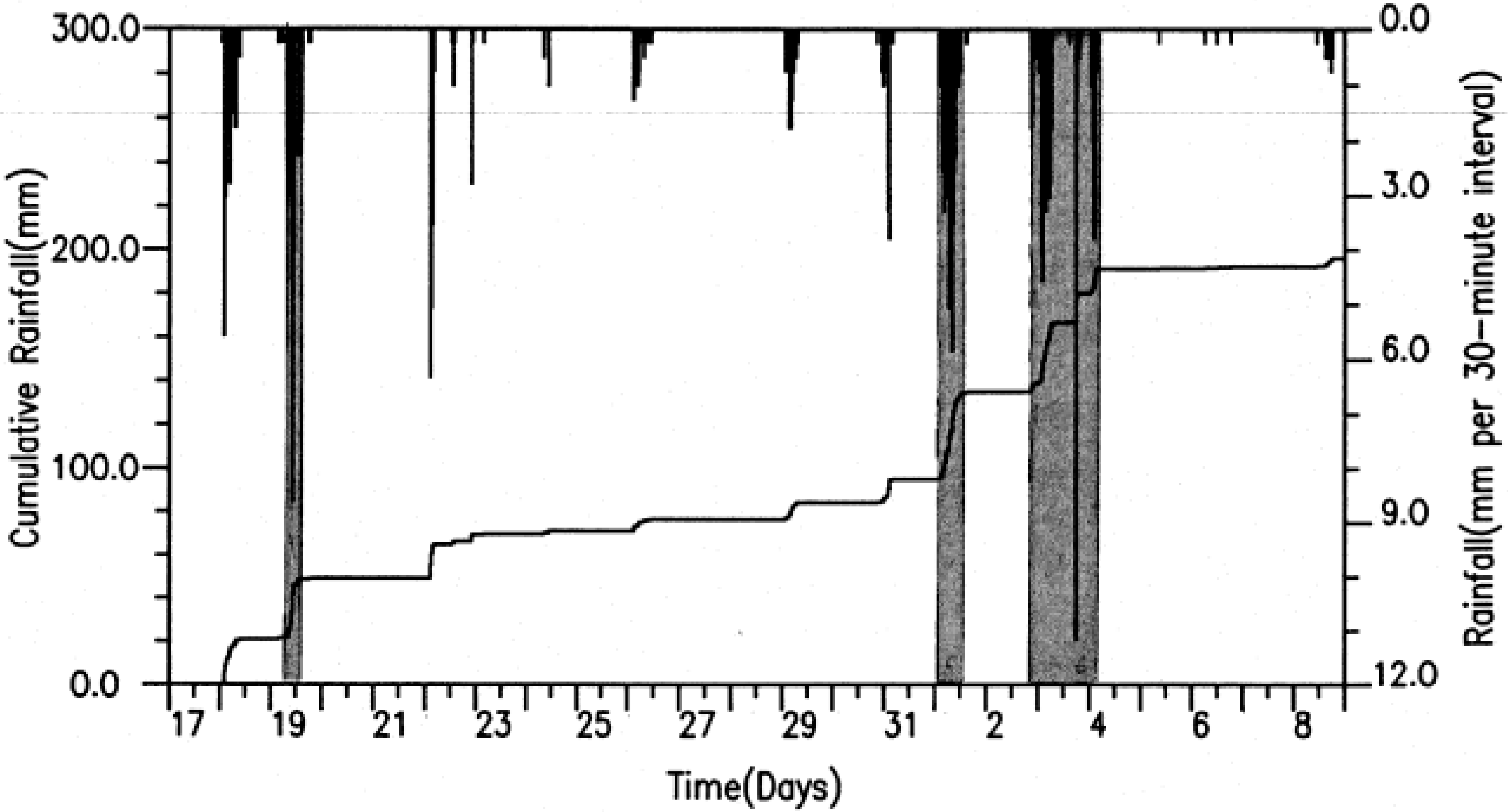


Figure B-14. Cumulative Rainfall and Rainfall Intensity for Storms 4-6, Covering Period 12/17/86 to 01/09/87.

Appendix C. Stream Discharge, Pipe Transect Discharge, Cumulative Rainfall, and Rainfall Intensity Data for Storms 7-10.

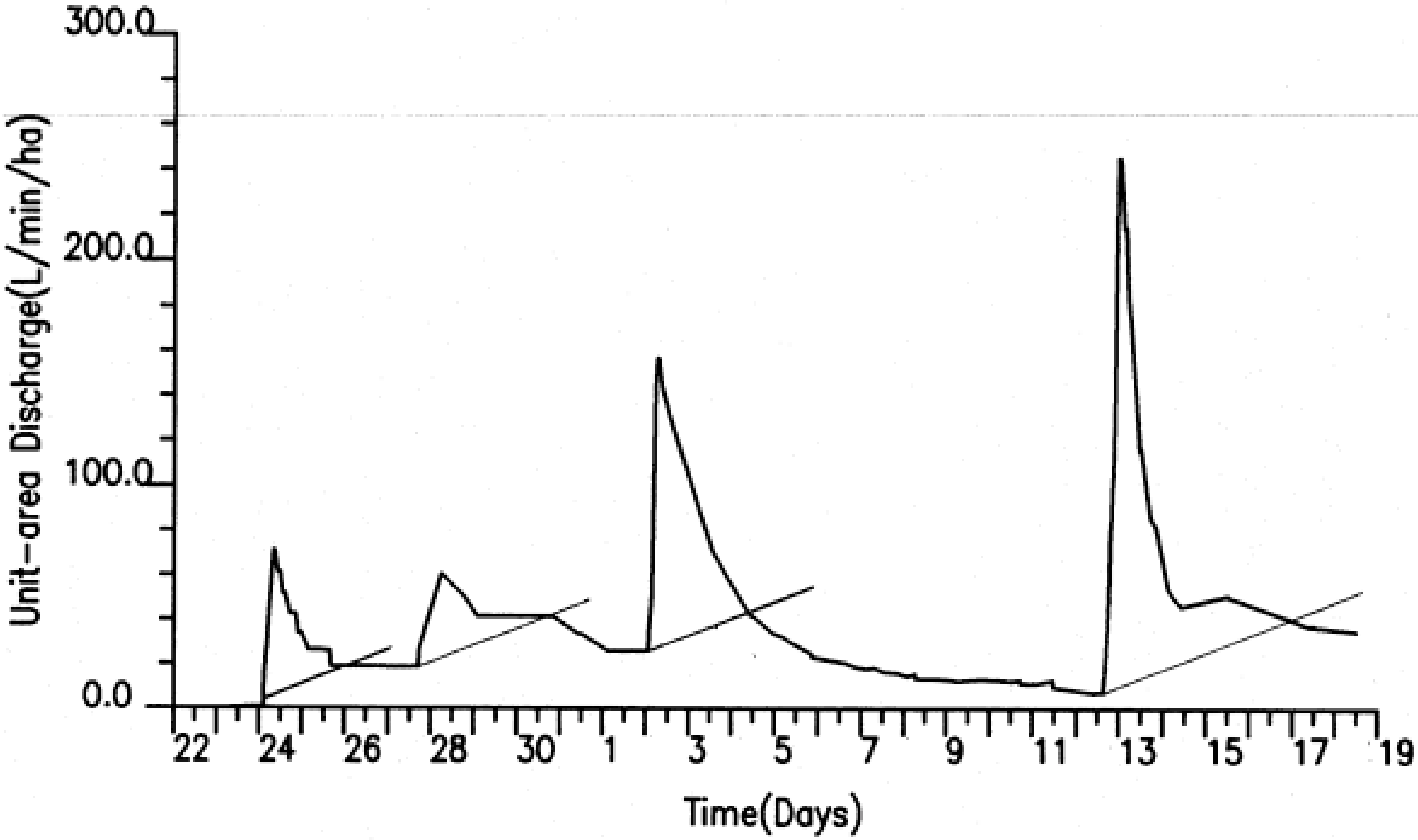


Figure C-15. Discharge at Stream Site MUN for Storms 7-10, Covering Period 01/22/87 to 02/19/87.

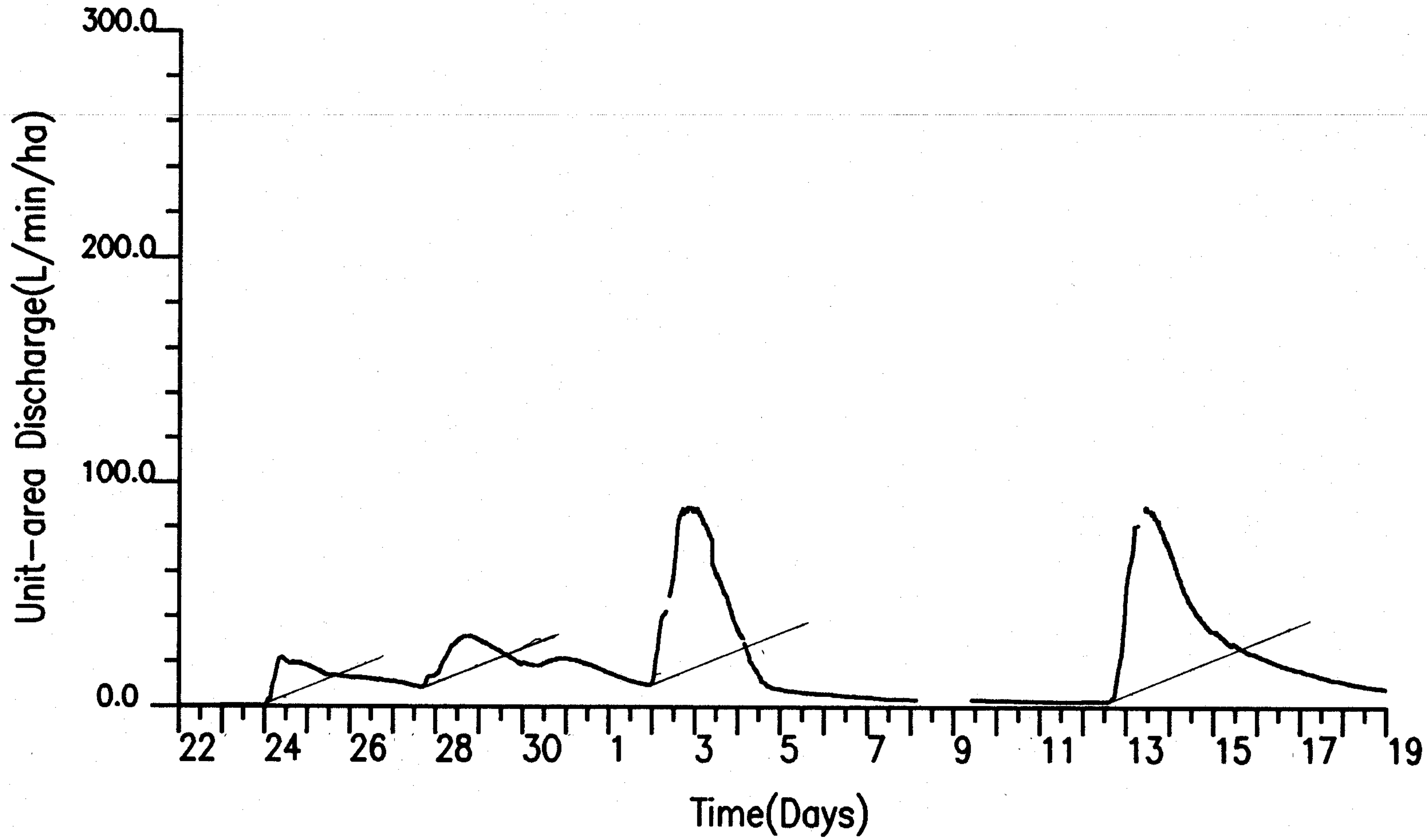


Figure C-16. **Discharge at Piping Site M1 for Storms 7-10, Covering Period 01/22/87 to 02/19/87.**

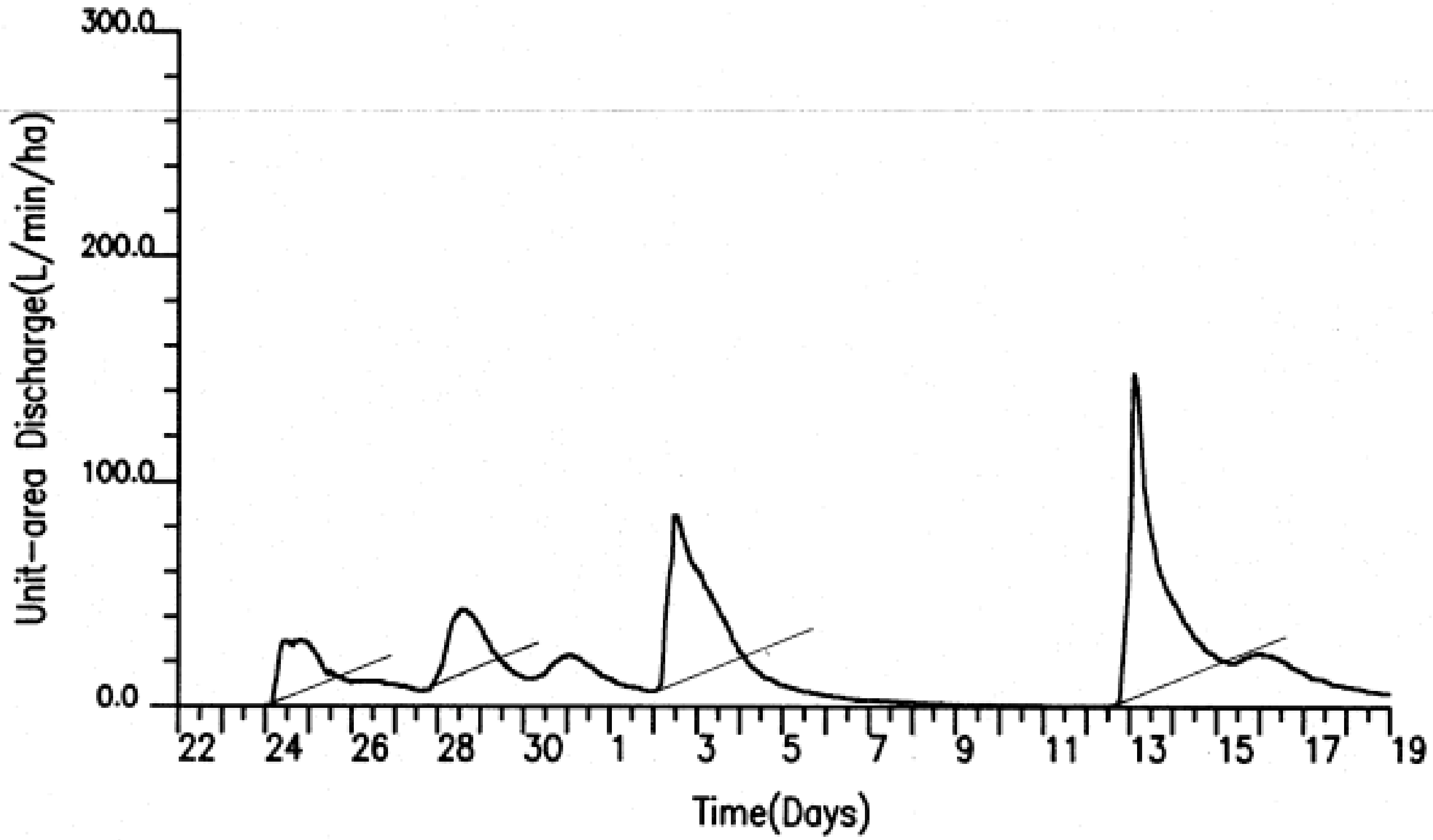


Figure C-17. Discharge at Piping Site K1 for Storms 7-10, Covering Period 01/22/87 to 02/19/87.

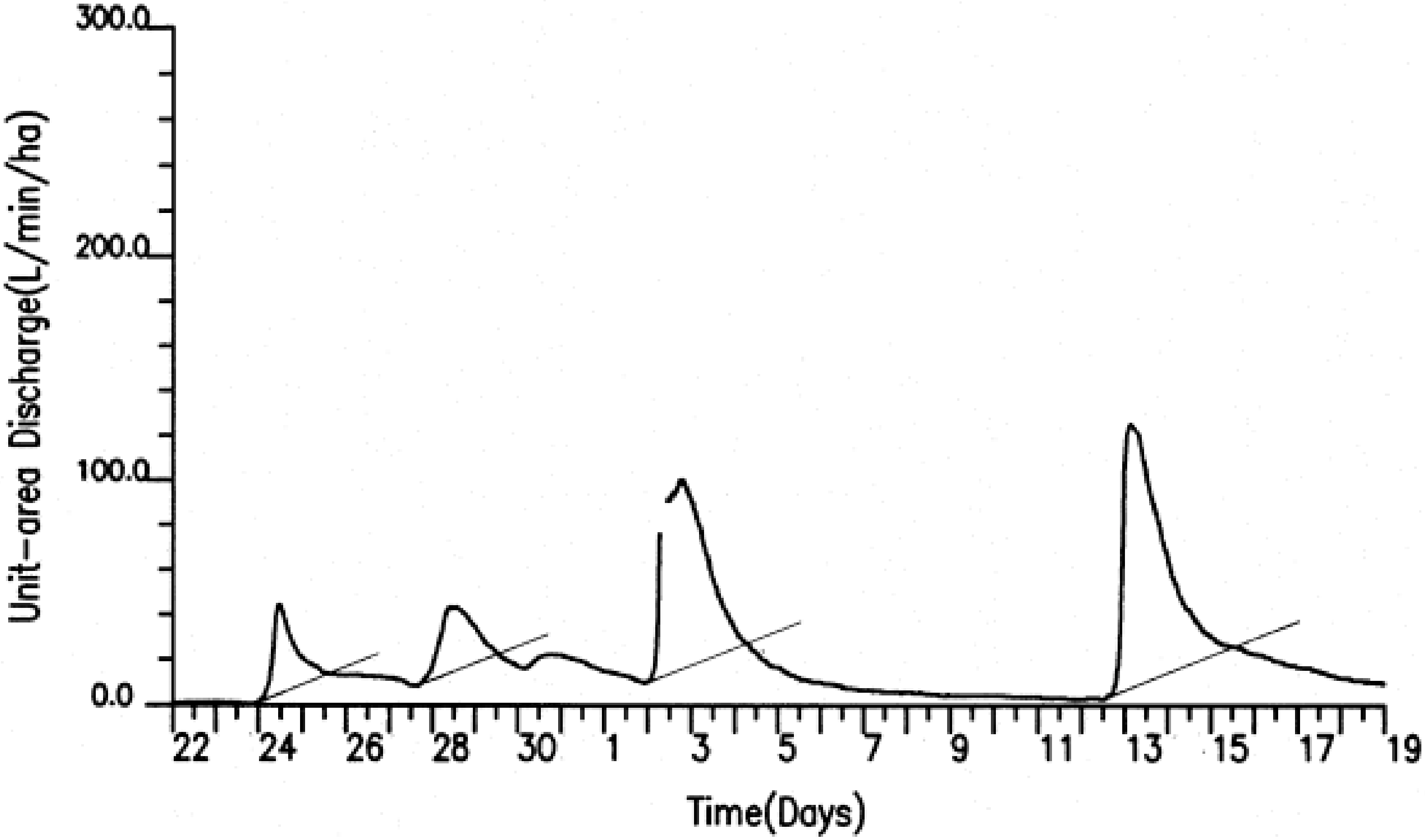


Figure C-18. Discharge at Piping Site K2 for Storms 7-10, Covering Period 01/22/87 to 02/19/87.

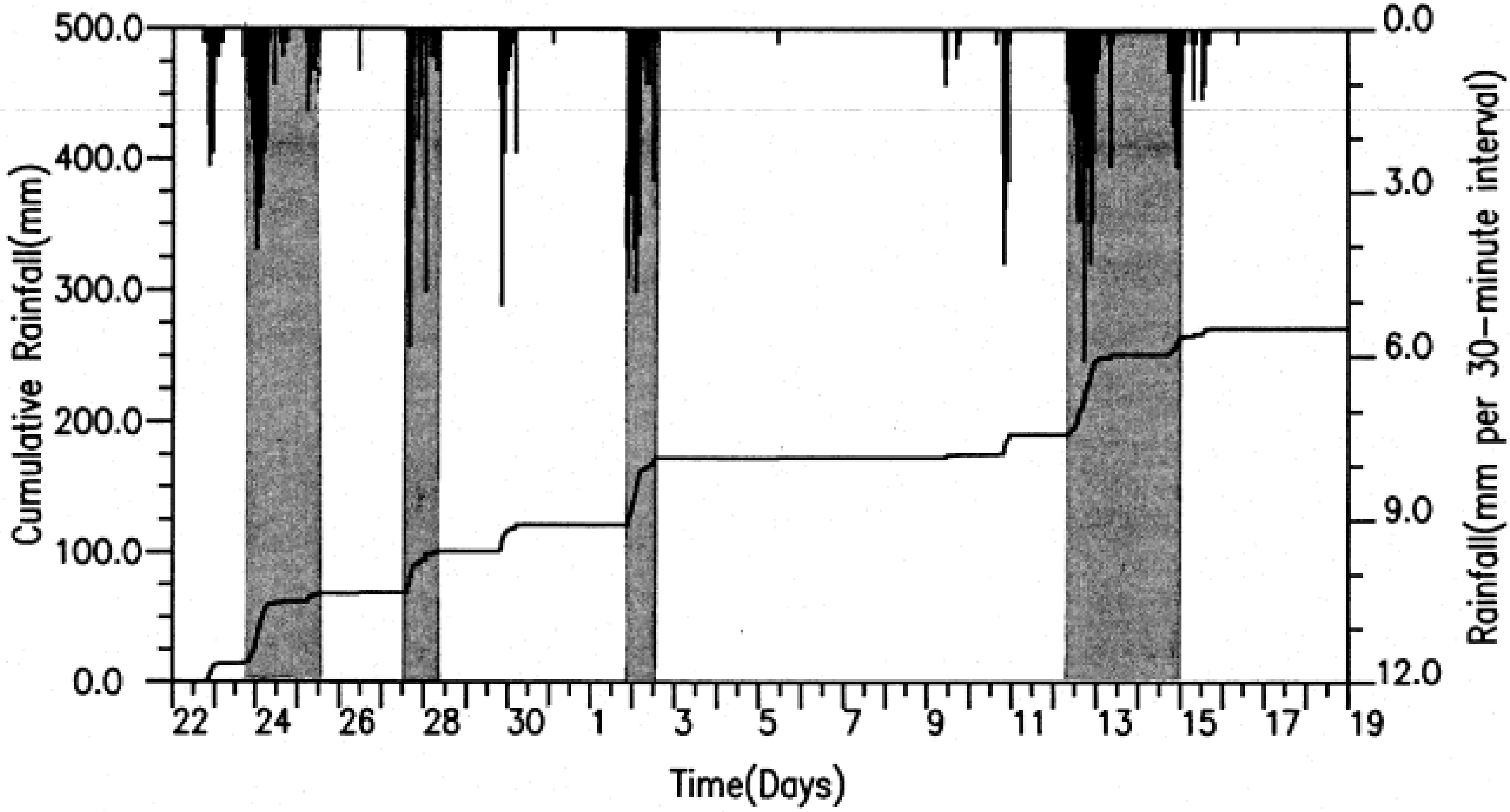


Figure C-19. Cumulative Rainfall and Rainfall Intensity for Storms 7-10, Covering Period 01/22/87 to 02/19/87.

Appendix D. Stream Discharge, Pipe Transect Discharge, Cumulative Rainfall, and Rainfall Intensity Data for Storms 11-14.

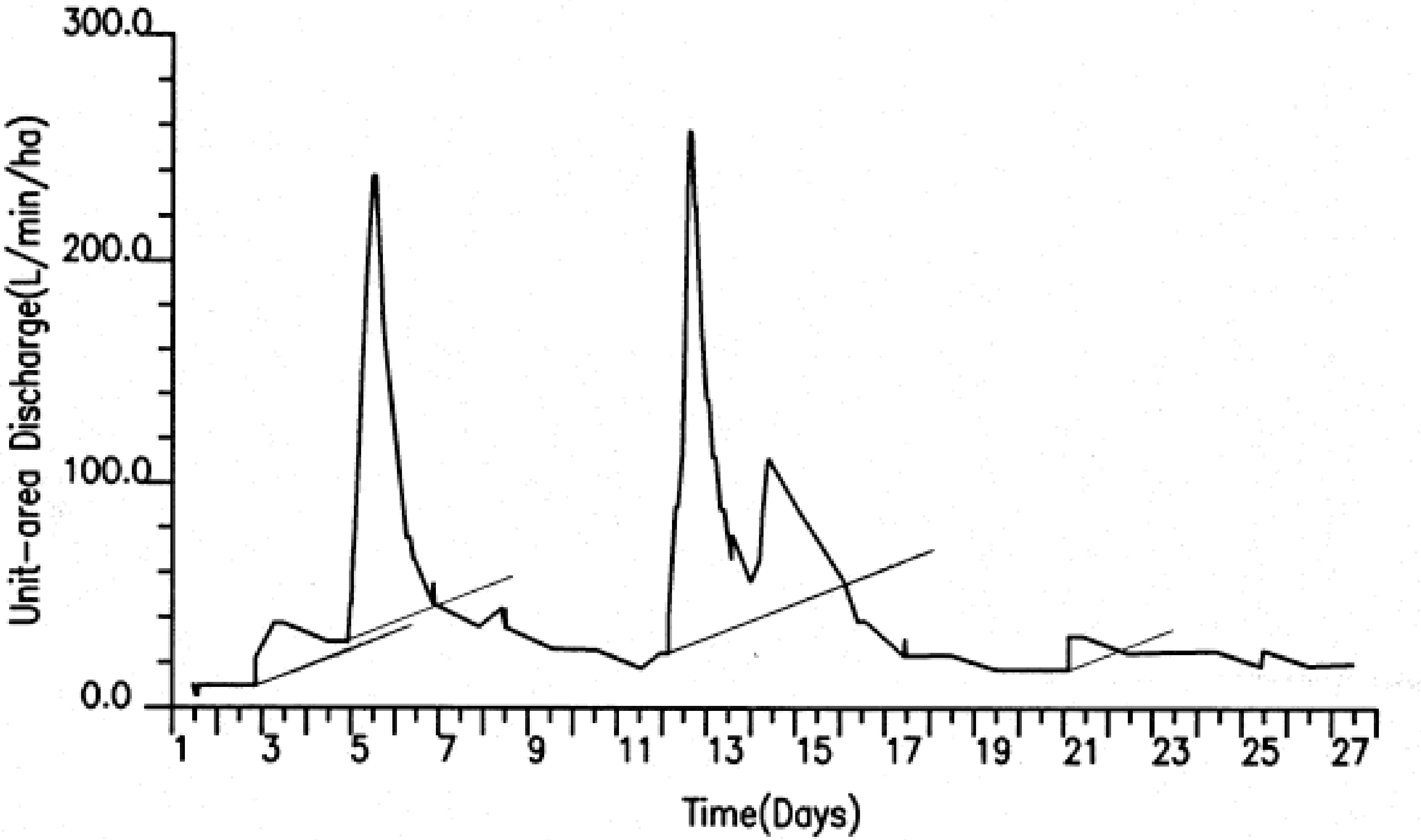


Figure D-20. **Discharge at Stream Site MUN for Storms 11-14, Covering Period 03/01/87 to 03/28/87.**

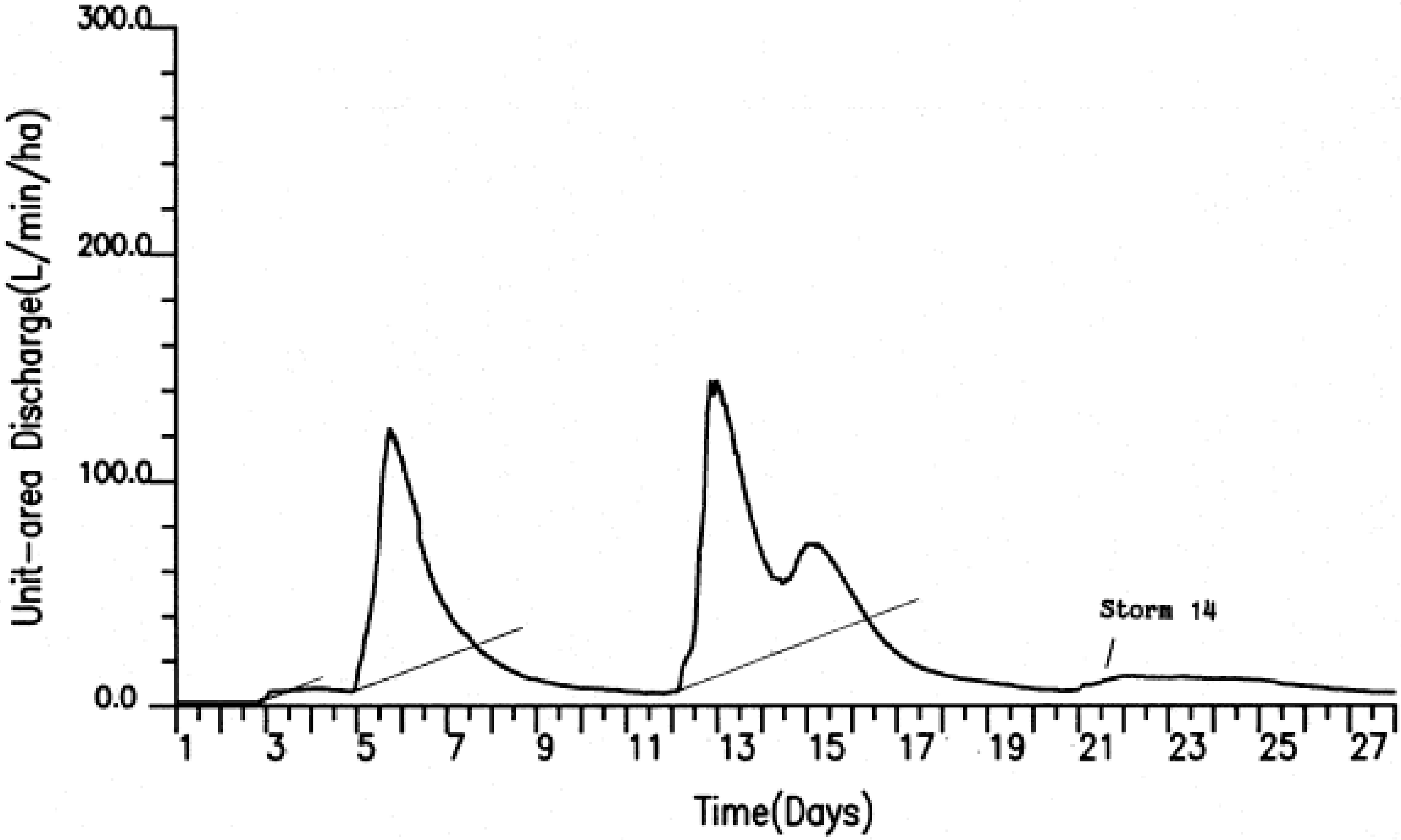


Figure D-21. Discharge at Piping Site M1 for Storms 11-14, Covering Period 03/01/87 to 03/28/87.

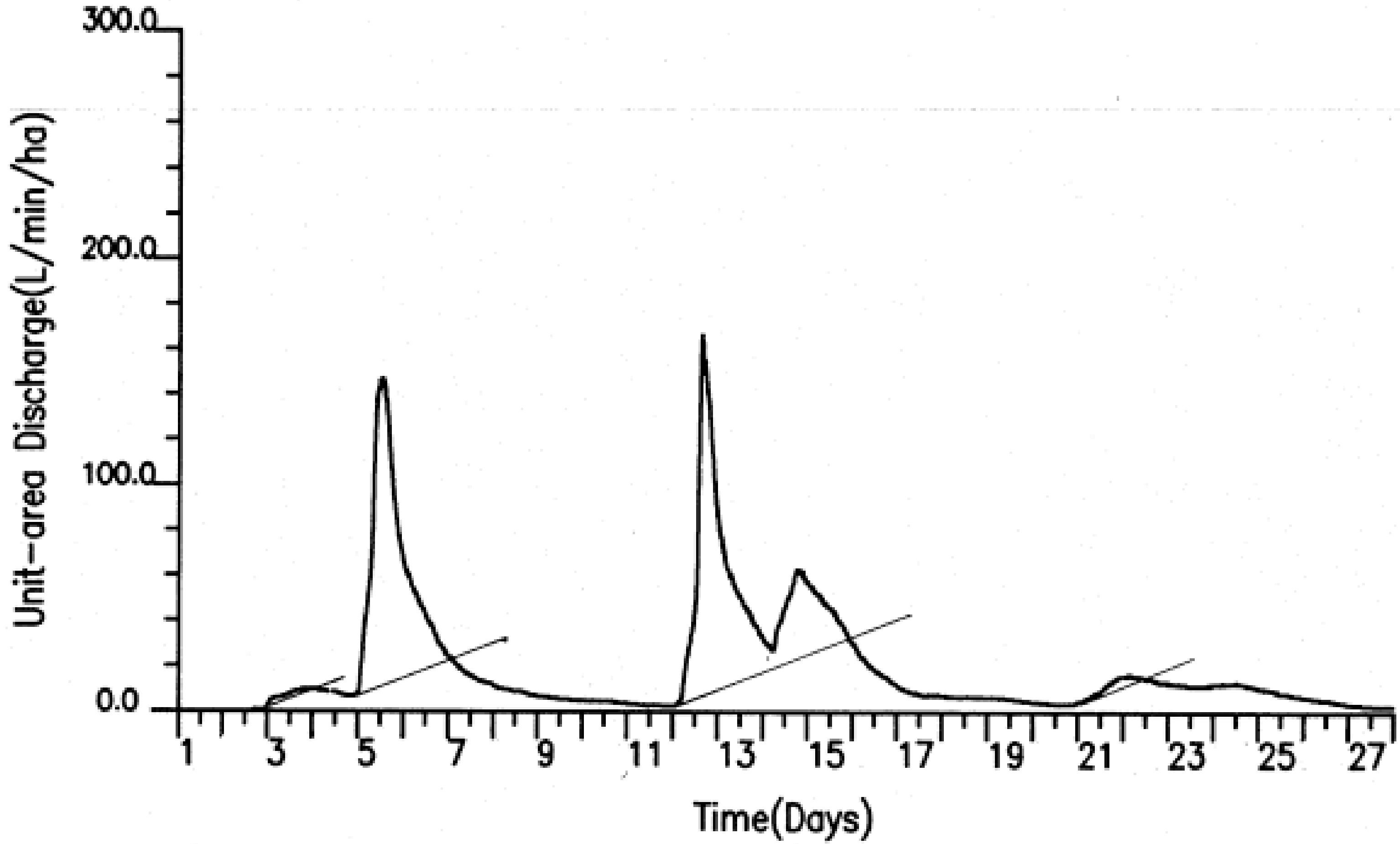


Figure D-22. **Discharge at Piping Site K1 for Storms 11-14, Covering Period 03/01/87 to 03/28/87.**

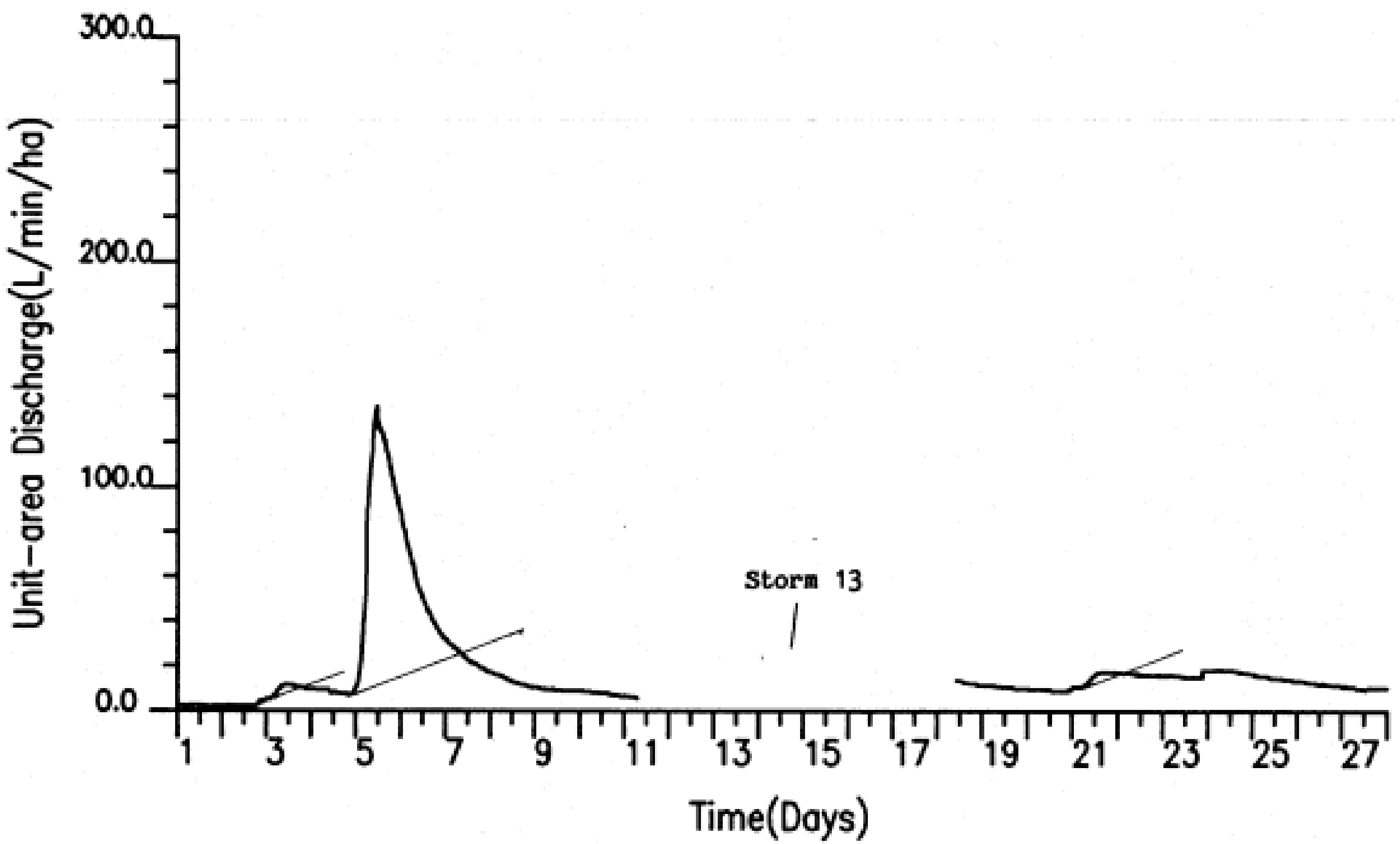


Figure D-23. **Discharge at Piping Site K2 for Storms 11-14, Covering Period 03/01/87 to 03/28/87.**

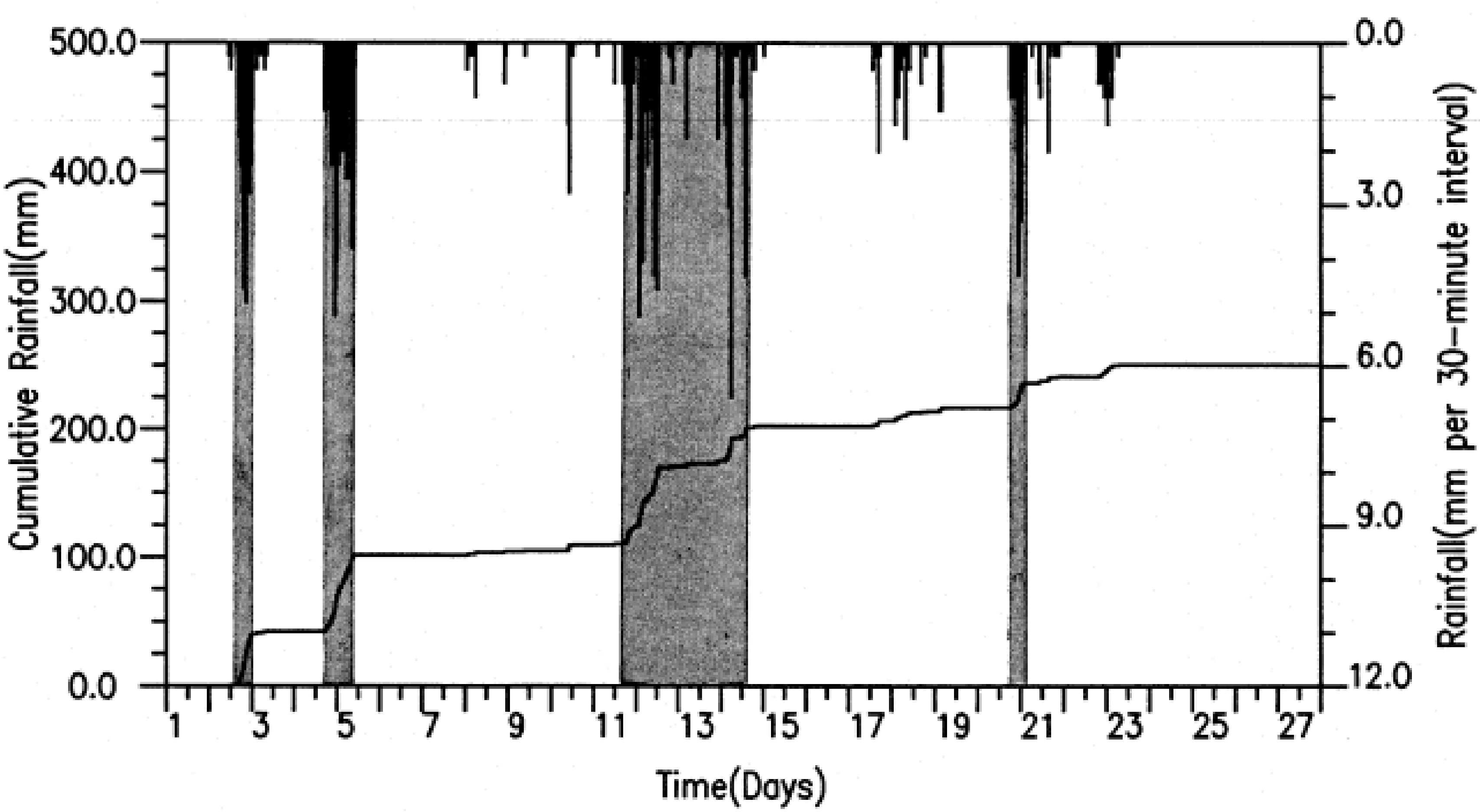


Figure D-24. **Cumulative Rainfall and Rainfall Intensity for Storms 11-14, Covering Period 03/01/87 to 03/28/87.**

Appendix E. Stream Discharge, Pipe Transect Discharge, Cumulative Rainfall, and Rainfall Intensity Data for Storms 15-19.

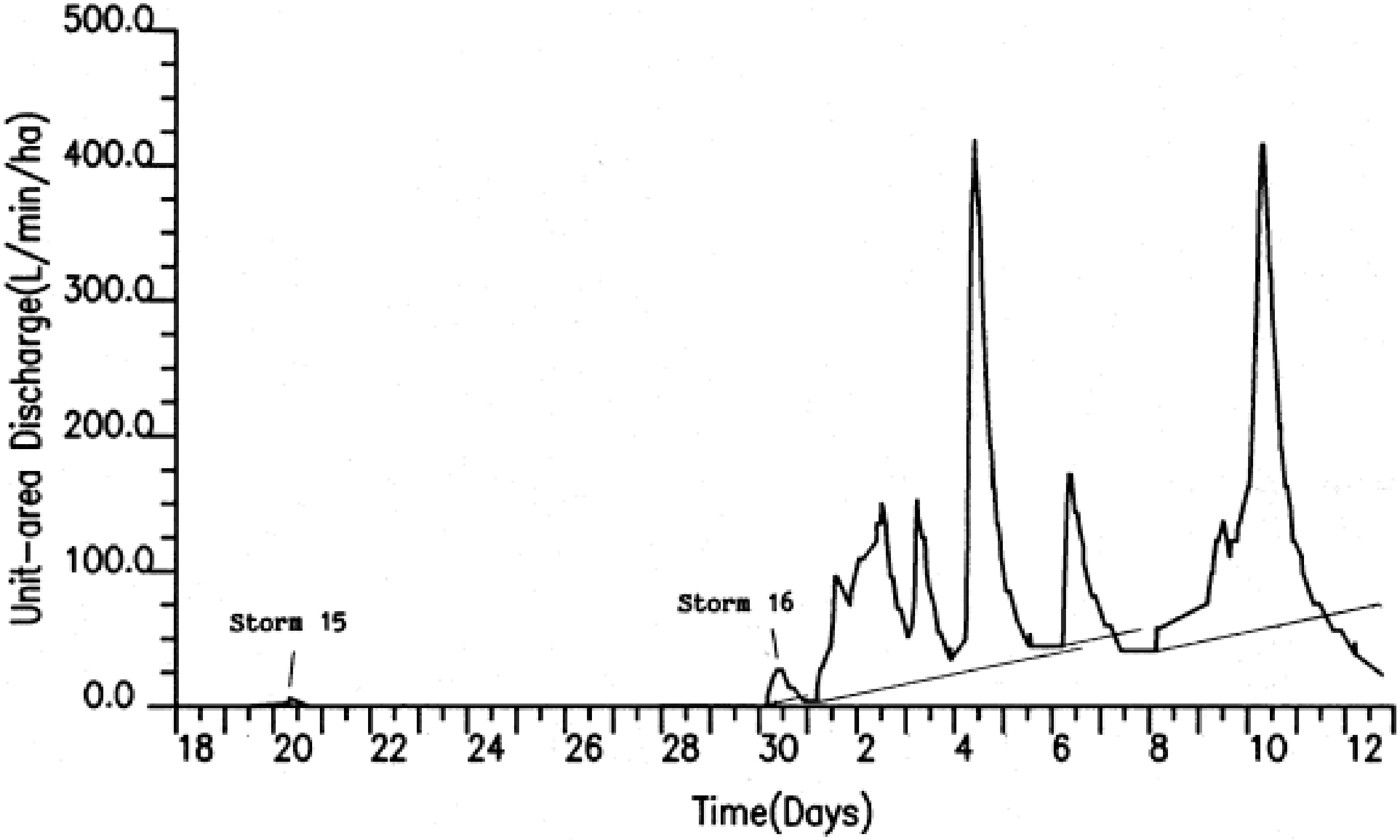


Figure E-25. **Discharge at Stream Site MUN for Storms 15-19, Covering Period 11/18/87 to 12/13/87.**

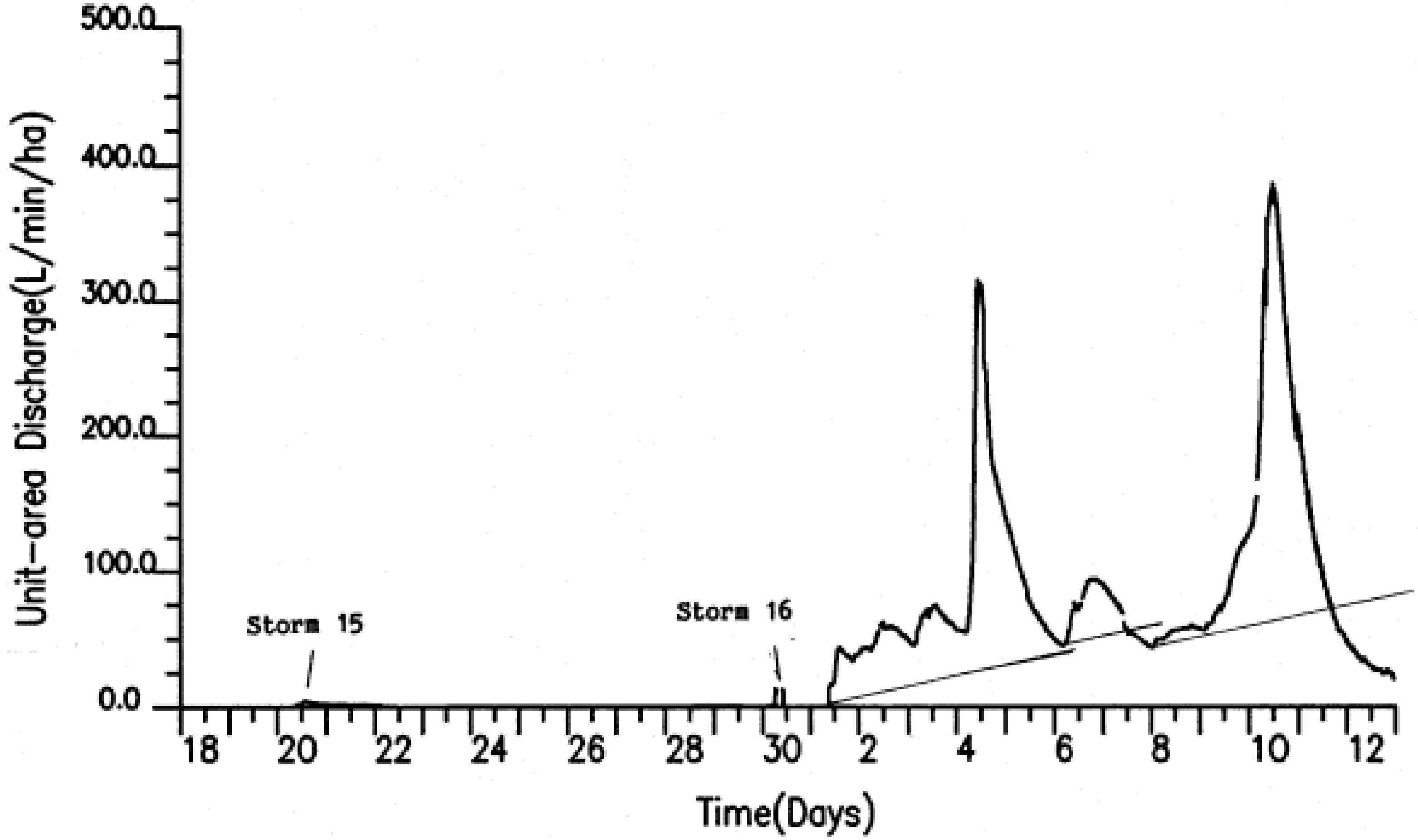


Figure E-26. Discharge at Piping Site M1 for Storms 15-19, Covering Period 11/18/87 to 12/13/87.

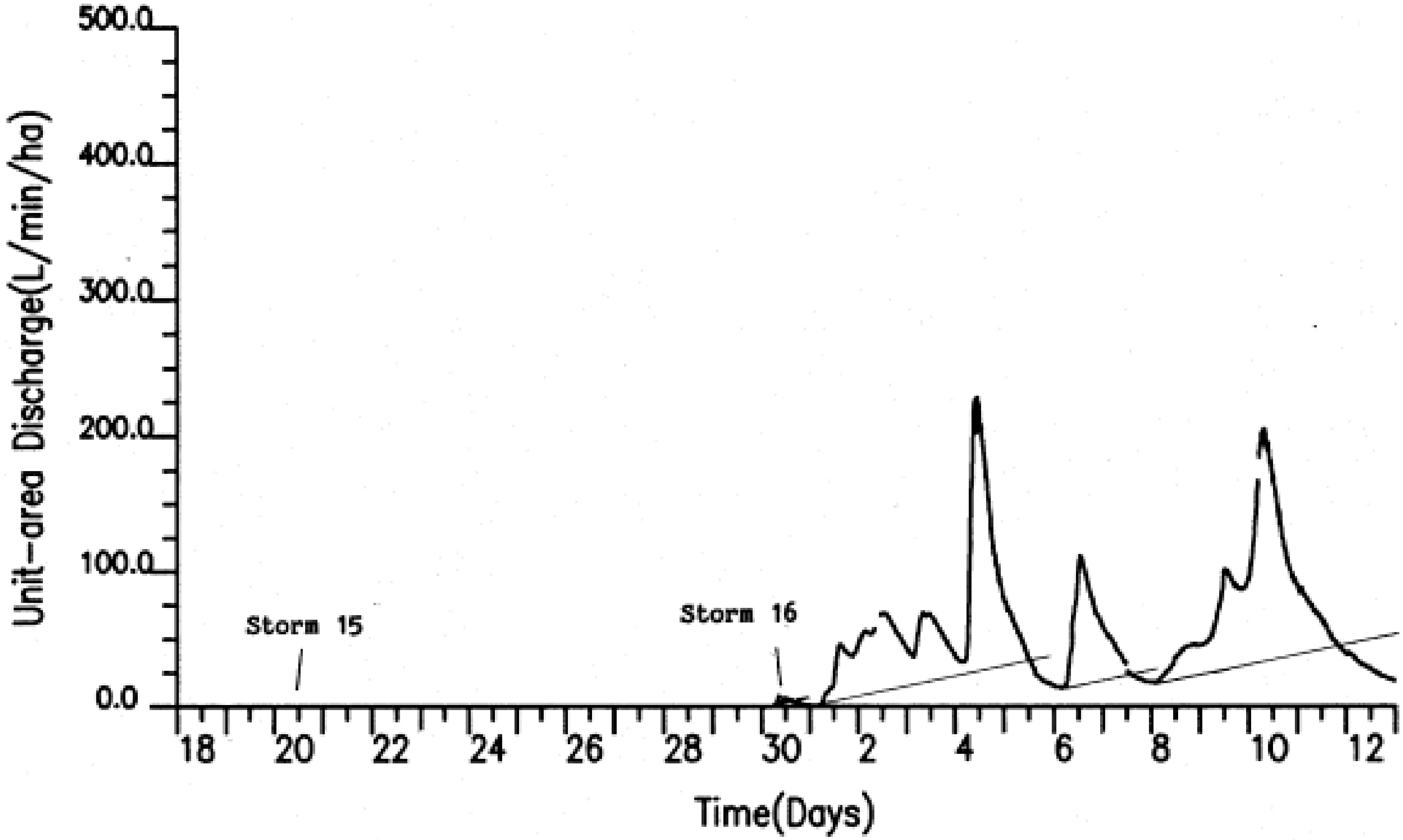


Figure E-27. Discharge at Piping Site K1 for Storms 15-19, Covering Period 11/18/87 to 12/13/87.

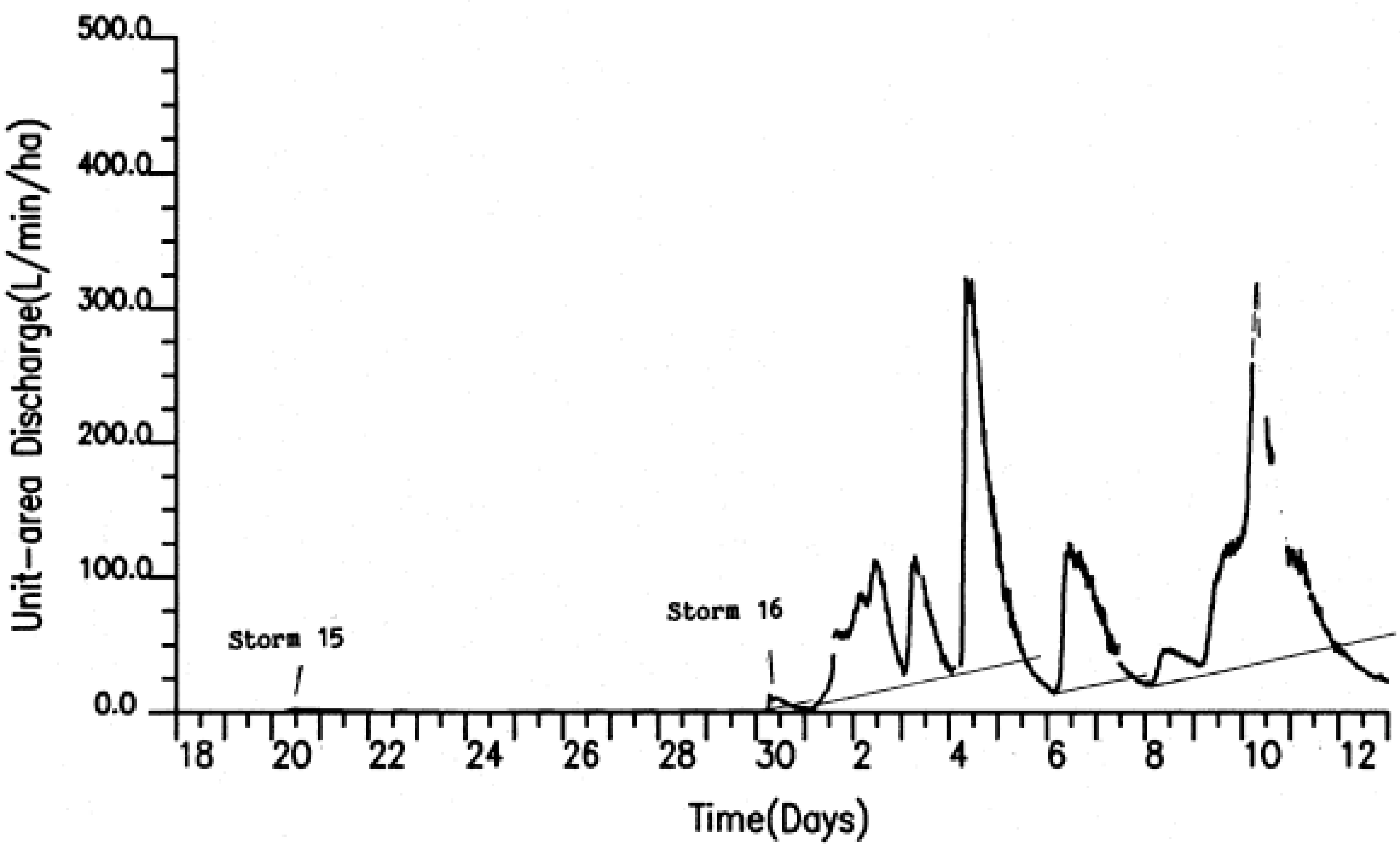


Figure E-28. **Discharge at Piping Site K2 for Storms 15-19, Covering Period 11/18/87 to 12/13/87.**

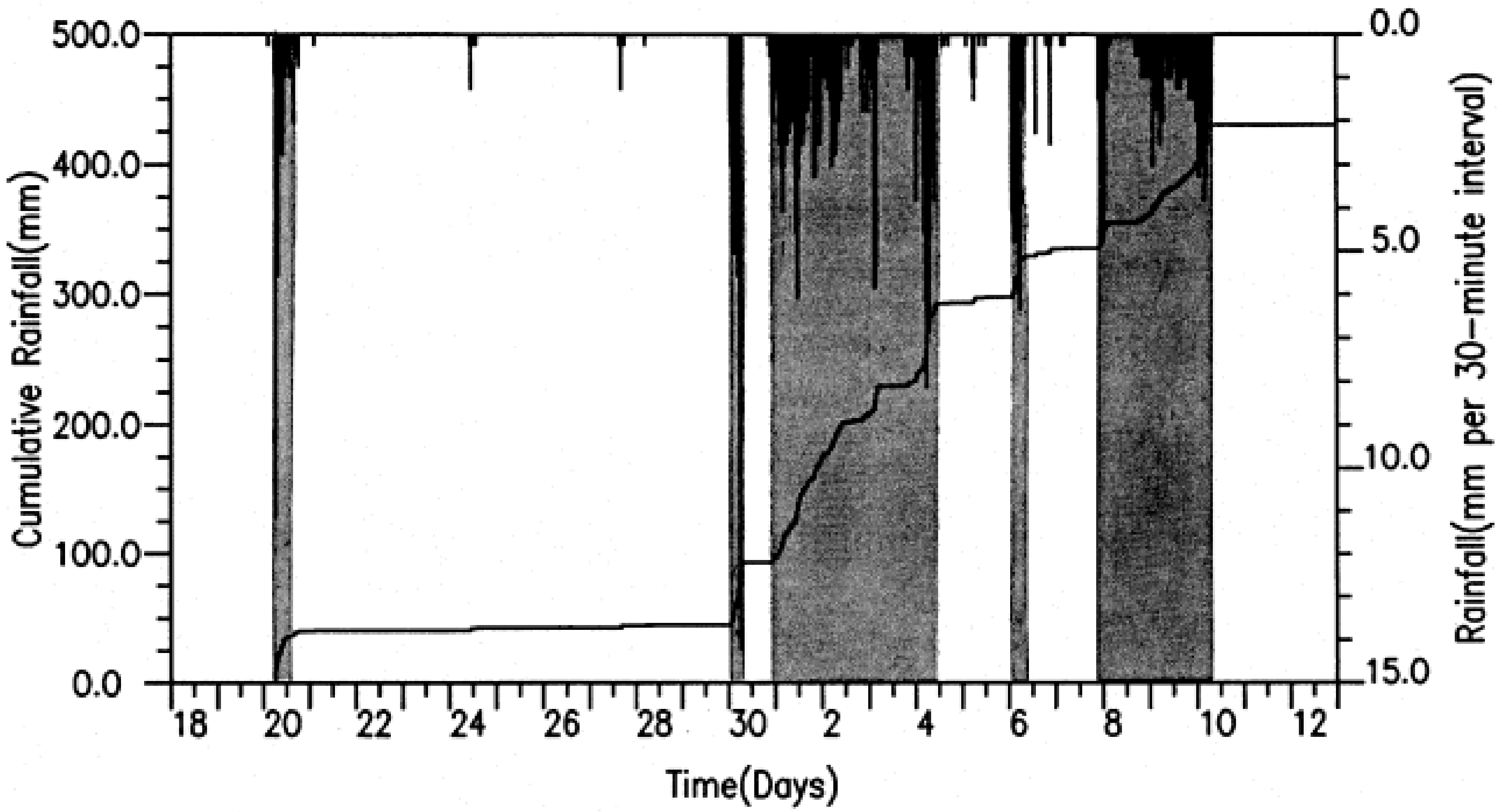


Figure E-29. Cumulative Rainfall and Rainfall Intensity for Storms 15-19, Covering Period 11/18/87 to 12/13/87.

Appendix F. Stream Discharge, Pipe Transect Discharge, Cumulative Rainfall, and Rainfall Intensity Data for Storms 20-22.

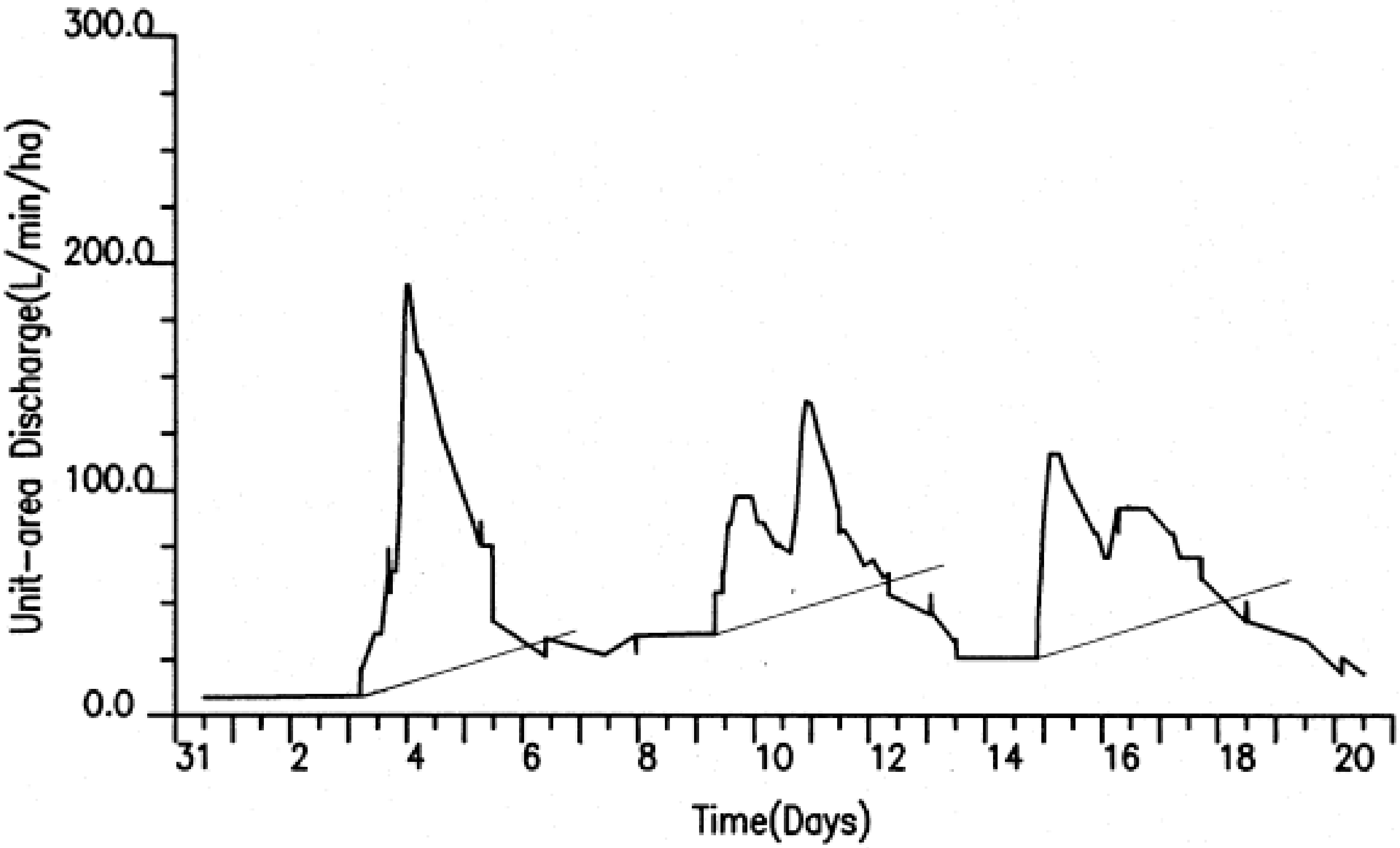


Figure F-30. Discharge at Stream Site MUN for Storms 20-22, Covering Period 12/31/87 to 01/21/88.

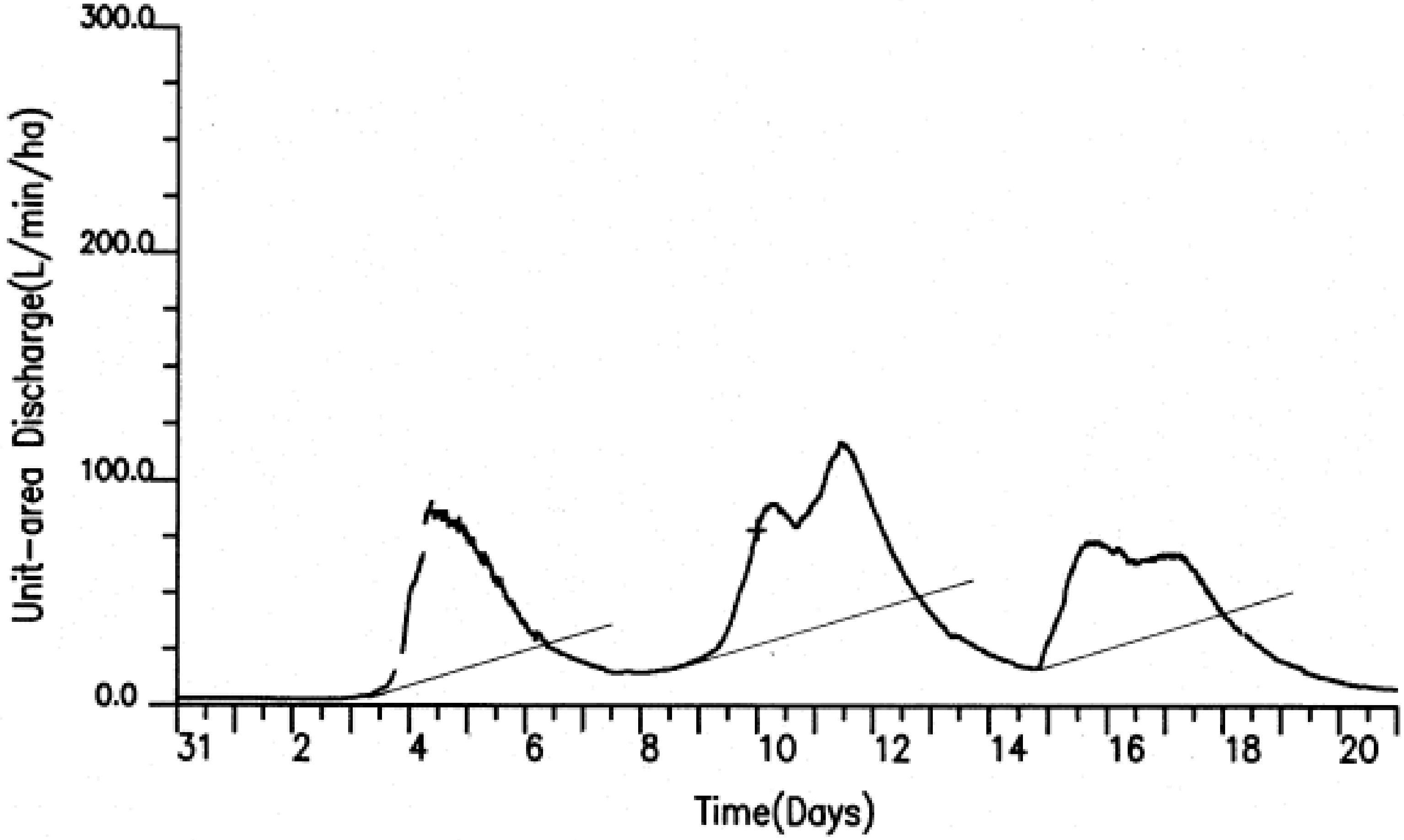


Figure F-31. **Discharge at Piping Site M1 for Storms 20-22, Covering Period 12/31/87 to 01/21/88.**

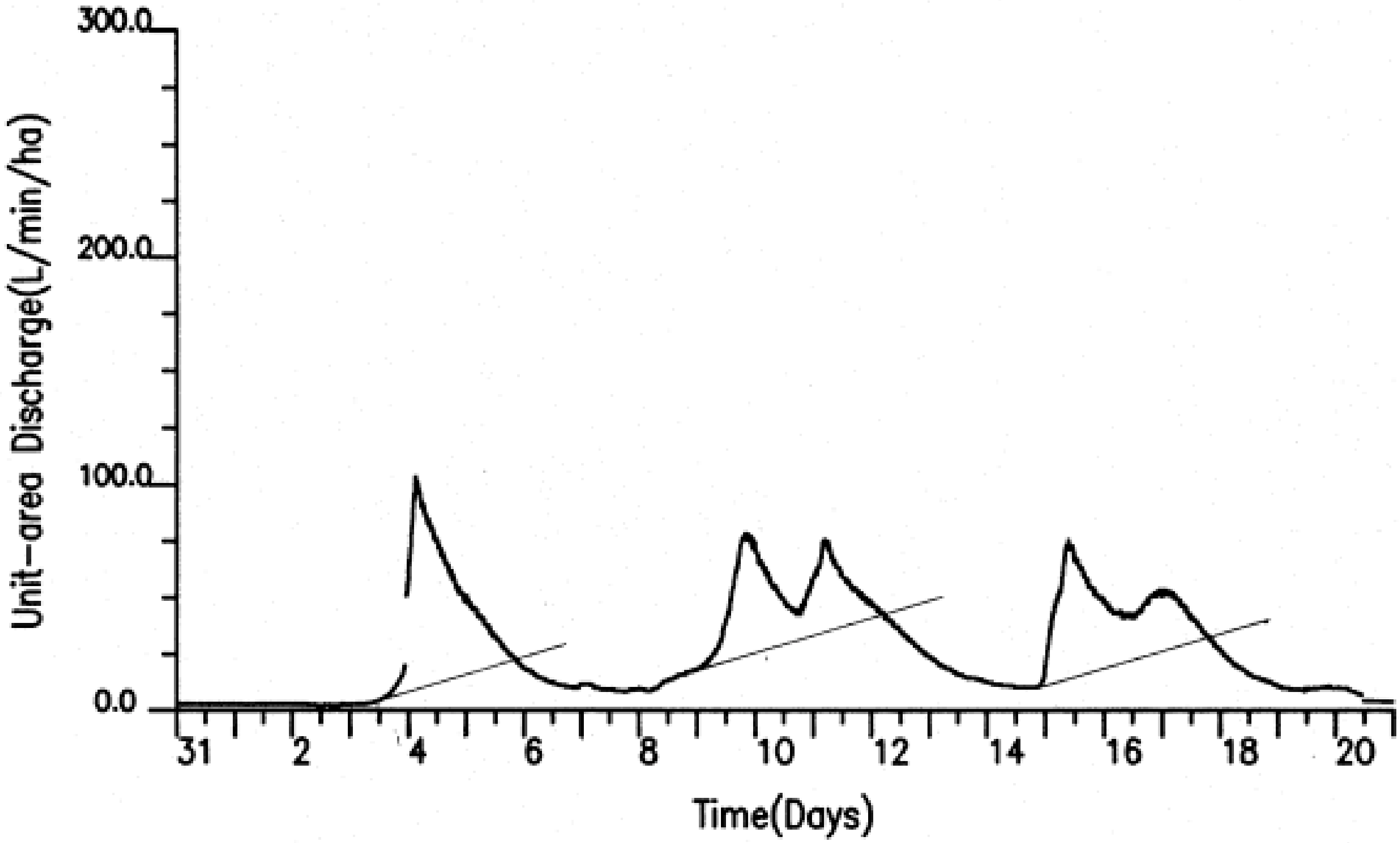


Figure F-32. Discharge at Piping Site K1 for Storms 20-22, Covering Period 12/31/87 to 01/21/88.

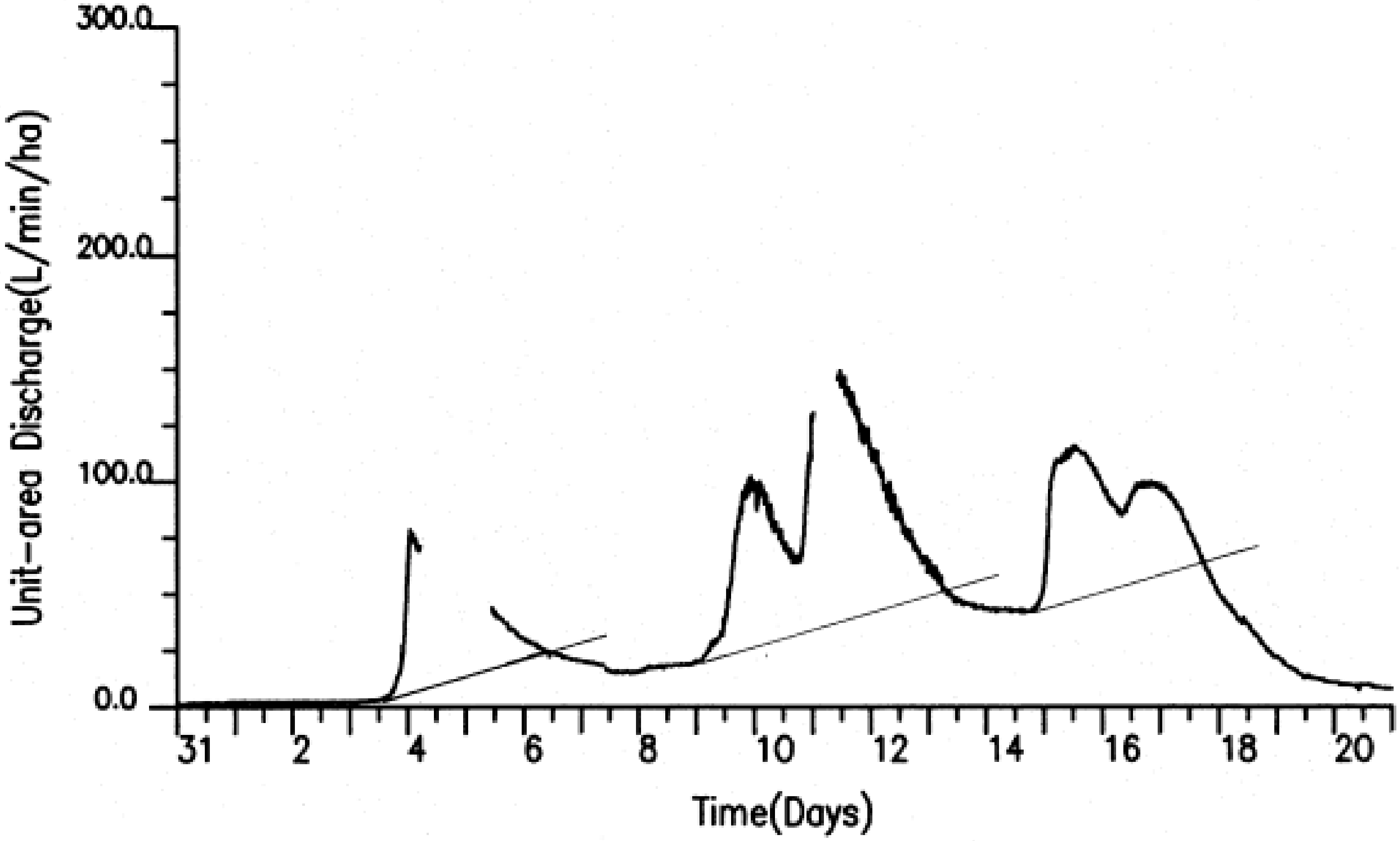


Figure F-33. Discharge at Piping Site K2 for Storms 20-22, Covering Period 12/31/87 to 01/21/88.

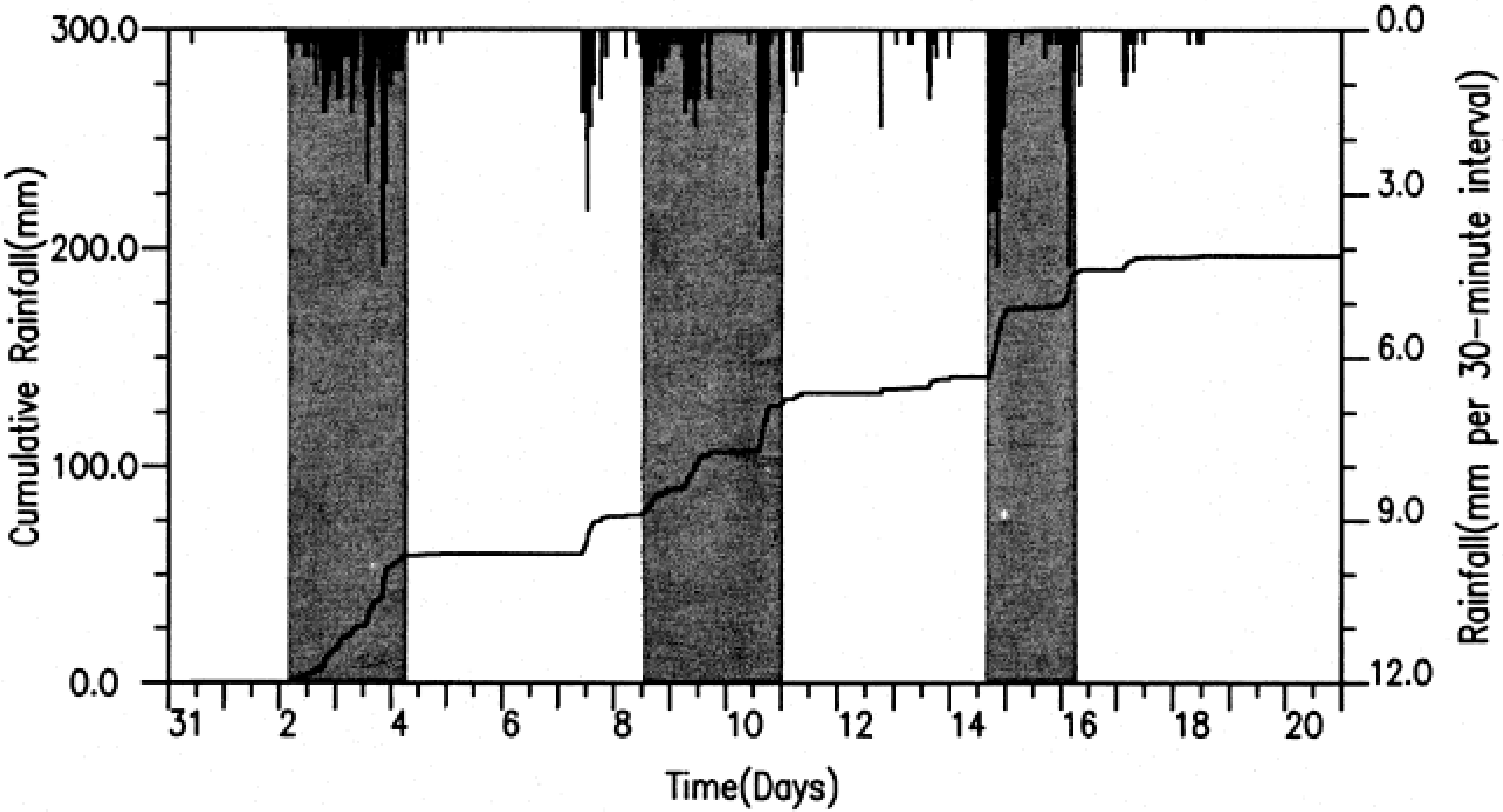


Figure F-34. **Cumulative Rainfall and Rainfall Intensity for Storms 20-22, Covering Period 12/31/87 to 01/21/88.**

Appendix G. Dotplots Indicating Spread and Distribution for Variables Used in T-tests.

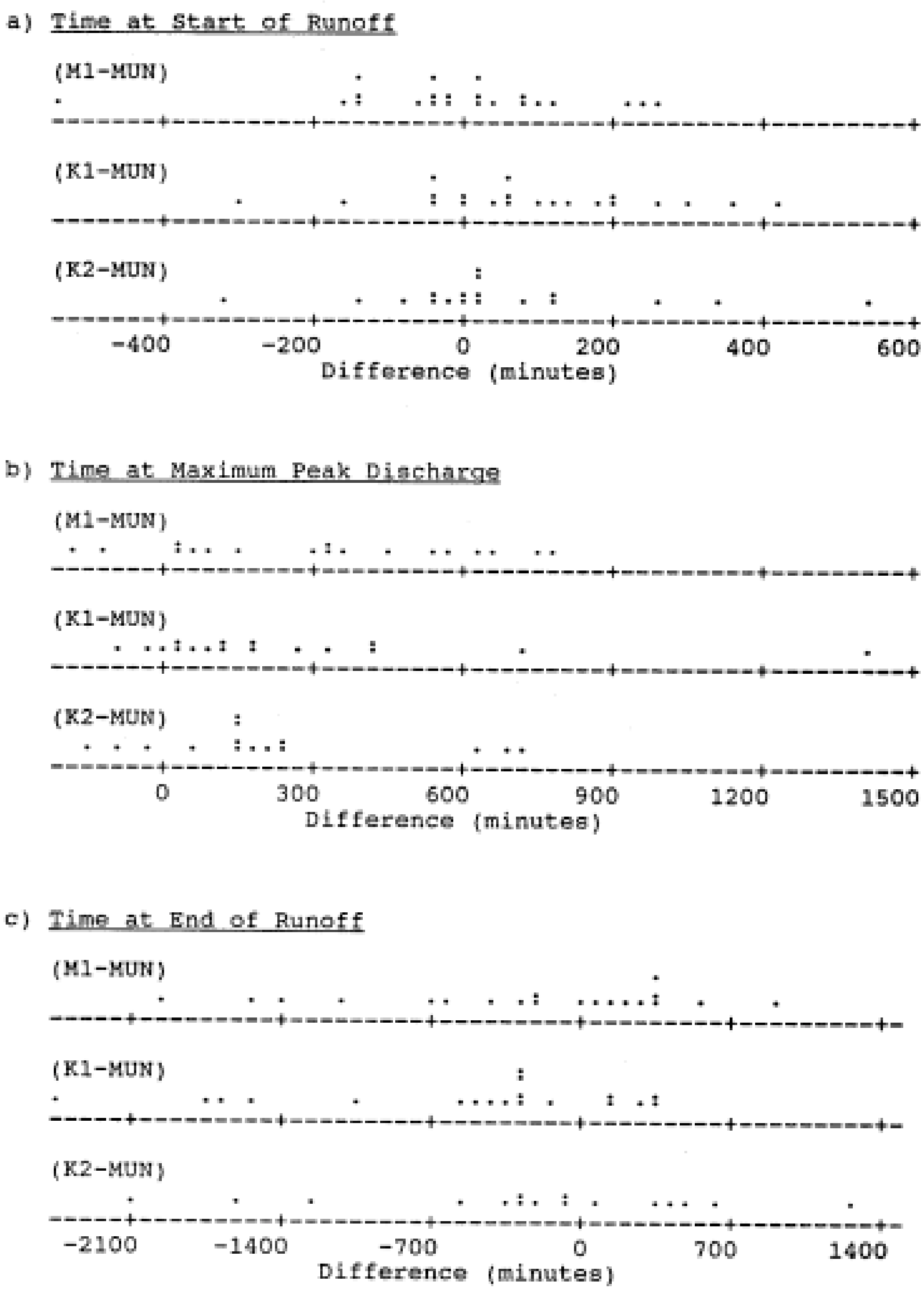
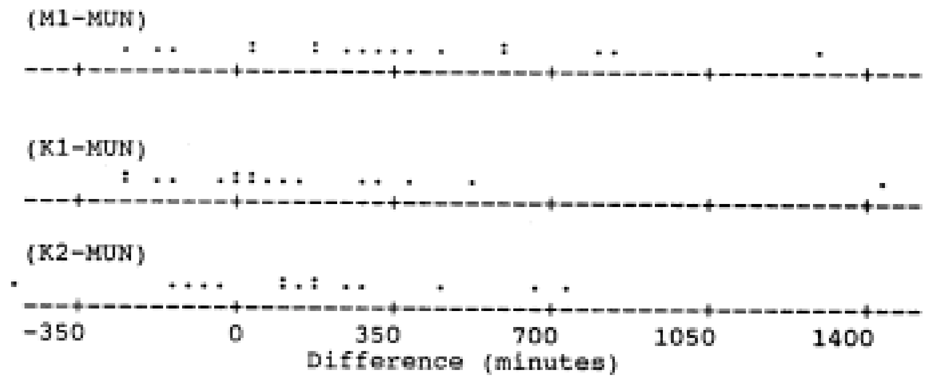


Figure G-35. Dotplots for Timing Parameters.

Appendix G. Dotplots Indication Spread and Distribution for Variables Used in T-tests (continued).

a) Duration from Start to Maximum Peak Discharge



b) Duration from Start of Runoff to End of Runoff

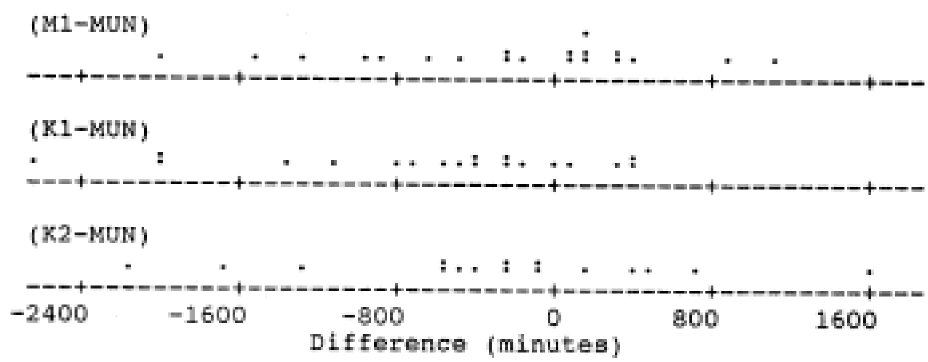


Figure G-36. Dotplots for Duration Parameters.

Appendix G. Dotplots Indicating Spread and Distribution for Variables Used in T-tests (continued).

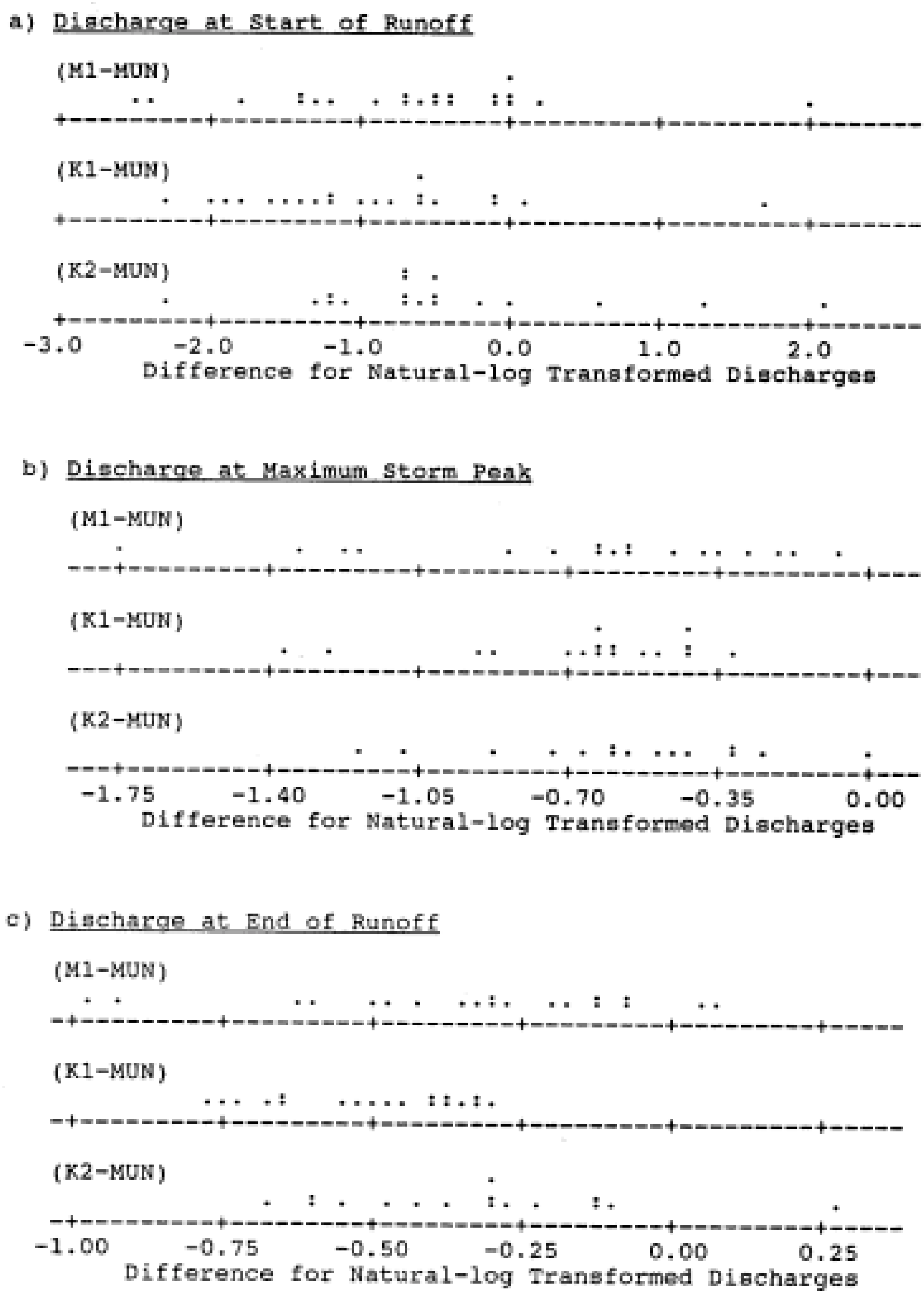
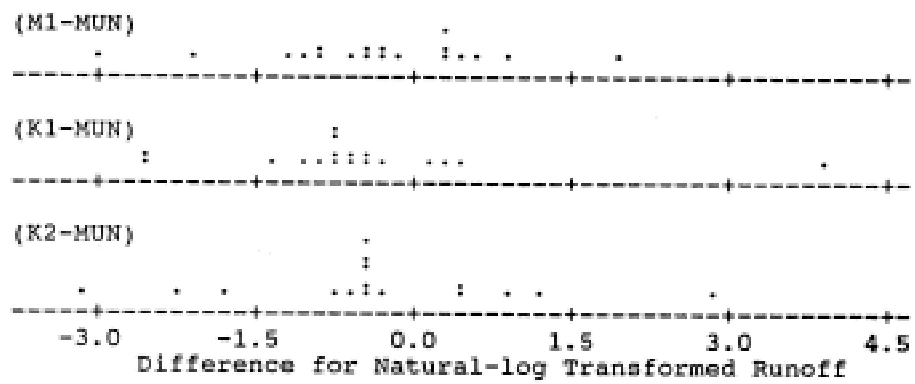


Figure G-37. Dotplots for Discharge Parameters.

Appendix G. Dotplots Indicating Spread and Distribution for Variables Used in T-tests (continued).

a) Cumulative Runoff from Start of Runoff to Maximum Peak Discharge



b) Cumulative Runoff from Start of Runoff to End of Runoff

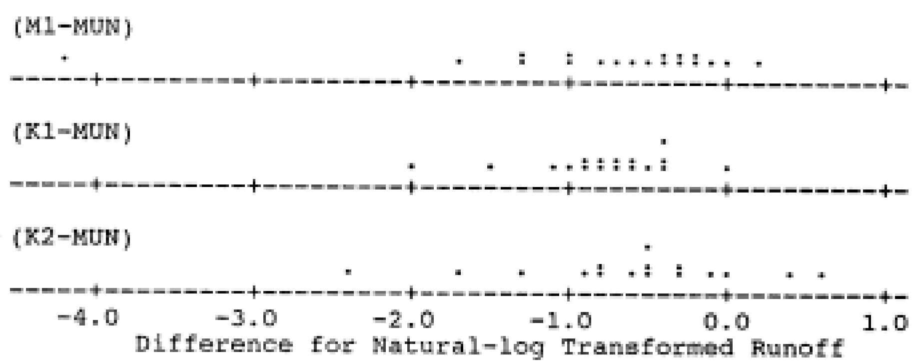


Figure G-38. Dotplots for Runoff Parameters.