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An isotopic study of the Palata Creek watershed, Lubombo area, eastern Swaziland.

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AN ISOTOPIC STUDY OF THE PALATA CREEK WATERSHED, LUBOMBO AREA, EASTERN SWAZILAND

by

Obed M. Ngwenya

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ABSTRACT

The main objective of this investigation was to examine storm runoff generation in the Palata Creek watershed in eastern Swaziland. Specifically, a suite of natural isotopic, chemical and hydrometric methods were used to assess groundwater contributions to storm runoff.

The Palata Creek watershed drains an area of 6.35 km^2. It is underlain by a massive rhyolite formation which is locally weathered. The average hydraulic conductivity of the weathered rhyolite as determined from single well tests in shallow wells is 1.0 x 10^{-7} m/s.

Soils in the catchment are generally thin, and range from sandy to silty clay. The soil has an average pH of 5.3. Organic content in the soil decreases with depth from 2.6% near the surface to 0.3% below 50 cm. The upper 50 cm of the soil contains numerous plant roots with occasional small diameter (less than 1.0 cm) macropores. The average hydraulic conductivity of the soil is 1.0 x 10^{-6} m/s.

During this research, the study area and the whole of southern Africa were affected by the worst drought in years. There were only three significant rainfall events in the catchment during this study. These events caused small rises in stream stages. Groundwater levels in shallow wells close to the stream channels increased very rapidly following each storm event. The groundwater levels in shallow wells located

away from the riparian areas were not affected by the rainfall events.

Oxygen-18 concentrations in rainfall, baseflow and stormflow, as well as hydrometric data were used to determine groundwater contributions to storm runoff in the catchment. Baseflow chemistry and isotopic composition matched that of shallow groundwater. The variability in the oxygen-18 content between rainfall events was large and it generated small but significant fluctuations in the stream isotopic composition. A simple mass balance hydrograph separation based on the oxygen-18 isotope concentrations during the first and second rainfall events showed that 70-80% of the peak flow was due to groundwater contribution in Palata Creek, and 85-90% in Nunzi Creek and at the confluence of Palata and Nunzi streams. The groundwater stage-groundwater discharge rating curve method also showed that groundwater contributed over 80% of the peak flow following each rainfall event in Palata Creek. The substantial groundwater contribution to streamflow during the storm events is believed to be caused by increased hydraulic gradients near or at the stream channels, which develop quickly after a rainfall event. The groundwater discharge also caused nitrate to increase from 6.6 mg/L to 18.9 mg/L in Palata Creek following the third storm event.

Both the chloride and electrical conductivity data in the baseflow and shallow groundwater showed no dilution by the rain water. Infact, a flushing effect occurred in which the electrical conductivity and chloride increased during the hydrograph rise. This type of flushing effect made chloride and electrical conductivity unsuitable as natural tracers for the mass balance hydrograph separation.

This work is dedicated to my family.

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My appreciation also go to the Department of Geological Surveys and Mines in Swaziland which provided the logistical support, including drilling, transport, camping facilities and chemical data analysis. The Soil Unit at the Agricultural Research Station at Malkerns in Swaziland is appreciated for helping with the soil analysis.

Mr. Allan Dakin of Piteau Associates Engineering Ltd, North Vancouver, B.C. provided some of the urgently needed technical data. I would also like to thank Charles Mhlanga, my field assistant who was very helpful in gathering most of the field data.

Thanks also go to friends and colleagues for their encouragement.

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1.0 INTRODUCTION

1.1 Background

This study was conducted in a small, but fairly densely populated and agriculturally productive catchment, in the Lubombo mountains in eastern Swaziland.

The main objective of the study was to assess the groundwater contributions to storm runoff in the streams of the area. This information is valuable in estimating the probable chemical composition of the stream waters. Estimates of groundwater runoff are also useful in determining the groundwater resources of a basin.

This rainfall-runoff study was affected by the unprecedented drought in the area. However, despite the extended dry periods observed during this study, groundwater drainage played an important role in maintaining streamflow in the catchment.

In 1988, a reconnaissance groundwater survey in the area was conducted by the Department of Geological Survey and Mines (DGSM) of Swaziland, assisted by consultants from Piteau Associates of North Vancouver, B.C. This study is part of that larger study, which was funded by the Canadian International Development Agency (CIDA).

1.2 Objectives and Scope of Study

The main objective of the research was to determine the contributions of groundwater to storm runoff events in the

Palata and Nunzi Creeks and at their confluence during the summer of 1992 (Southern Hemisphere). Other objectives of the study included: (1) to characterize the chemical and isotopic nature of the waters which contribute to storm runoff, and (2) to examine areal and temporal variations in water chemistry of the Palata catchment.

To meet these objectives, water samples were taken from sources which contribute to streamflow in the Palata Creek watershed, from January to March, 1992. Water samples were taken from springs, groundwater, rain, Palata and Nunzi streams and at their confluence. About 100 water samples were collected and later analyzed for chloride, nitrate, fluoride and oxygen-18. Selected samples were analyzed for deuterium. Electrical conductivity and pH of all samples were measured in the field.

The isotopic and chemical parameters were used in the steady state mass balance equations (Sklash, 1990) to determine the relative contributions of groundwater and rain water to the streams during storm events.

The storm hydrographs were also separated by relating groundwater stage to stream stage. Groundwater stage data were obtained from small-diameter shallow wells installed in the streambed and a few metres from the stream in one of the catchments. The hydrometric results were compared to those obtained from the chemical and isotope mass balance techniques.

1.3 Structure of the Thesis

The thesis has seven chapters. Chapter 1 describes the objectives and scope of the study. The study area is described in Chapter 2. This chapter provides information about location, climate, physiography, drainage, vegetation, land use, hydrology, geology and hydrogeology. Chapter 3 discusses the concepts of streamflow generation. Chapter 4 describes the principles of environmental isotopes (oxygen-18 and deuterium) and their applications in hydrogeologic studies. In Chapter 5, methods of study are discussed. This include information about precipitation and streamflow measurements, drilling methods, well installation, water level measurement, hydraulic conductivity measurement, soil analysis, water sample collection and analysis, and methods of hydrograph separation. Chapter 6 discusses the results of the investigations. The last chapter, Chapter 7, contains the conclusions and recommendations of the study.

2.0 STUDY AREA

2.1 Location and Access

Swaziland is a small country with an area of 17,353 km^2. Located in southern Africa, it has borders with the Republic of South Africa on the north, west and south; and with Mozambique on the east (Figure 1).

The study area is located at approximately latitude 26° 30'S and longitude 31° 58' E, about 16 km southeast of the small town of Siteki in eastern Swaziland (Figures 1 and 2) It is drained by the Palata and Nunzi creeks. Access to the area is easily made possible by the gravel road that connects Siteki town and the southeasternmost village of Mambane.

2.2 Climate

The climate in Swaziland as a whole is subtropical. Southeast trade winds provide summer rainfall to the area. The average annual rainfall is about 850 mm, and mean annual temperature is about 20 °C (MacDonald & Partners Ltd, 1990). The rainy season is from October to April, and the rest of the year is usually dry. The rainfall distribution is usually variable even during the rainy season.

2.3 Physiography and Drainage

The total area drained by the Palata and Nunzi creeks is about 6.35 km^2. The topography consists chiefly of

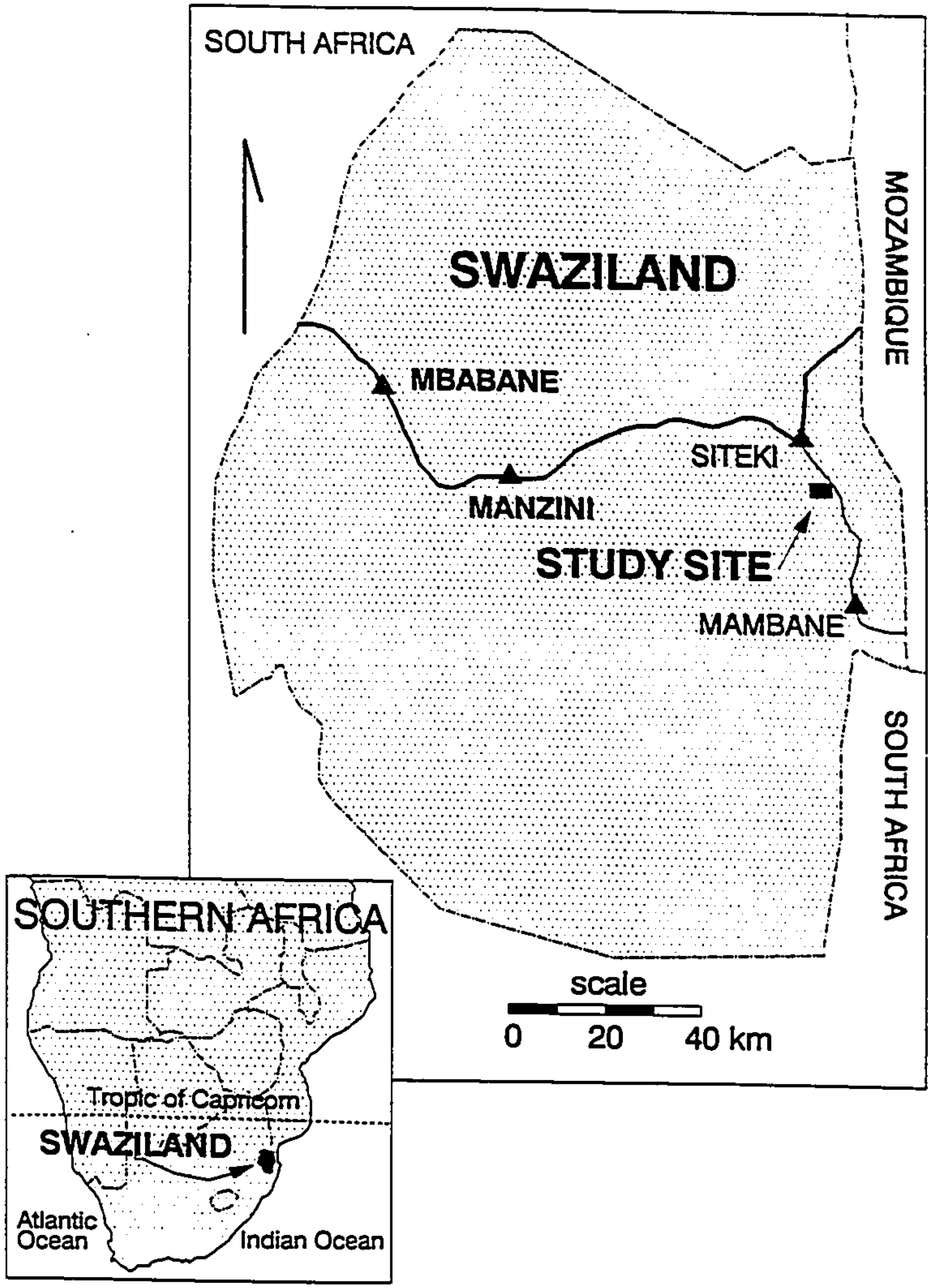

Figure 1. Location of study area.

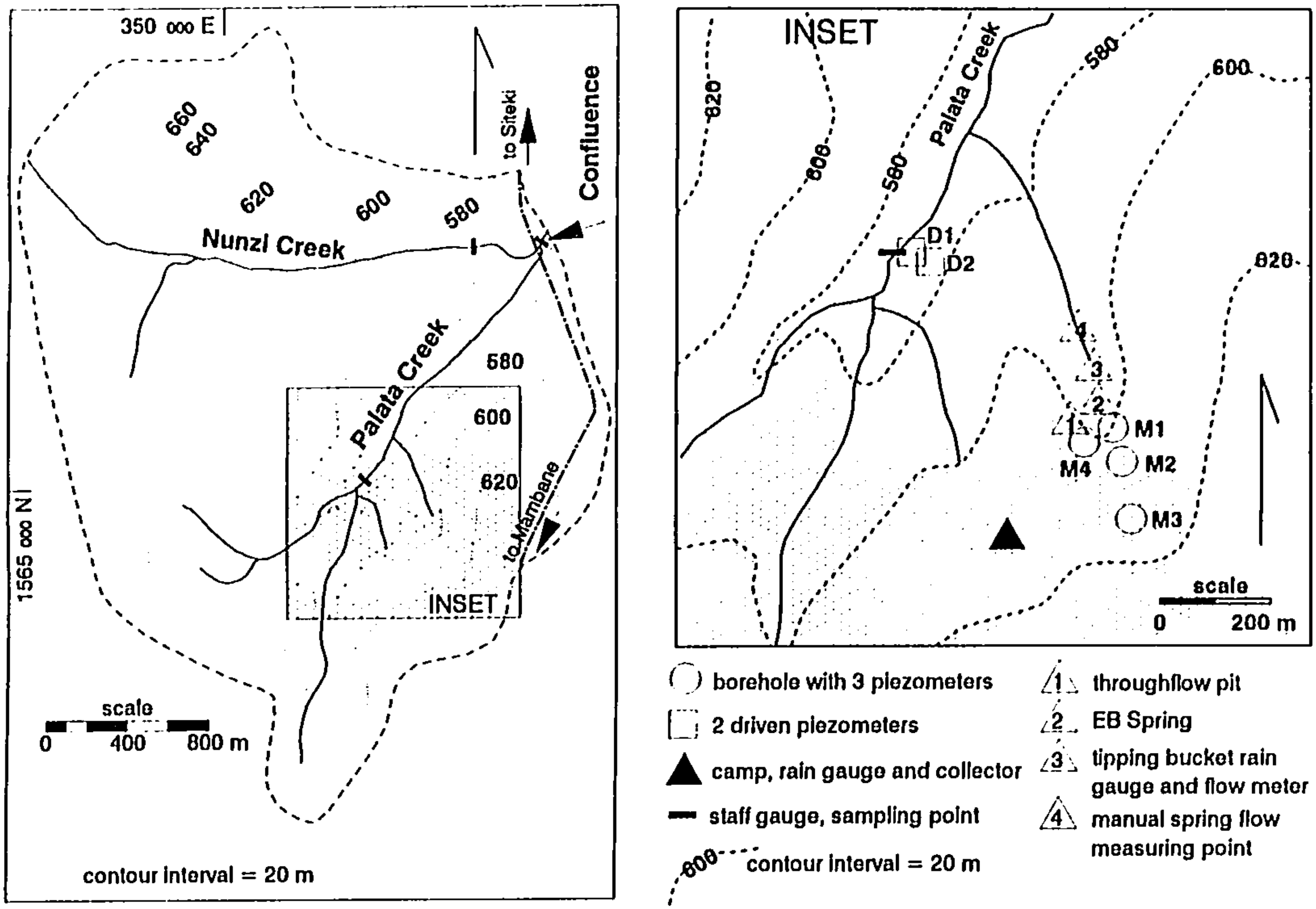

Figure 2. Instrumentation in the Palata Creek Watershed.

undulating uplands, with land surface elevations varying from 660 masl (metres above sea level) along upstream ridge tops to 555 masl at the lower end of the catchments where the two streams meet. Slopes to the streams vary from 6° to 10°. Drainage is generally east and northeastwards.

2.4 Vegetation and Land Use

Land use in the area is chiefly subsistence farming, with maize corn, sorghum, and cotton as the major crops (Figure 3). Livestock grazing also takes part in the area.

The agricultural practice in the catchment destroyed most of the natural trees except near the stream channels, where the vegetation consists of mixed bush and savanna.

2.5 Geology

2.5.1 Bedrock

Figure 4 is simplified bedrock geologic map of Swaziland. The study area is underlain by the rhyolites of the Karroo Supergroup of Upper Jurassic age. These rocks are described as 5 km thick acidic ignimbrite lavas, comprised of rhyolitic tuffs with quartz phenocrysts, and welded tuff agglomerates (Hunter, 1961; Wilson,1982). Cleverly and Bristow (1979) suggested that these rocks may have been deposited as devitrified or degassed ash flows

Figure 3. Land use and vegetation in the Palata Creek Watershed.

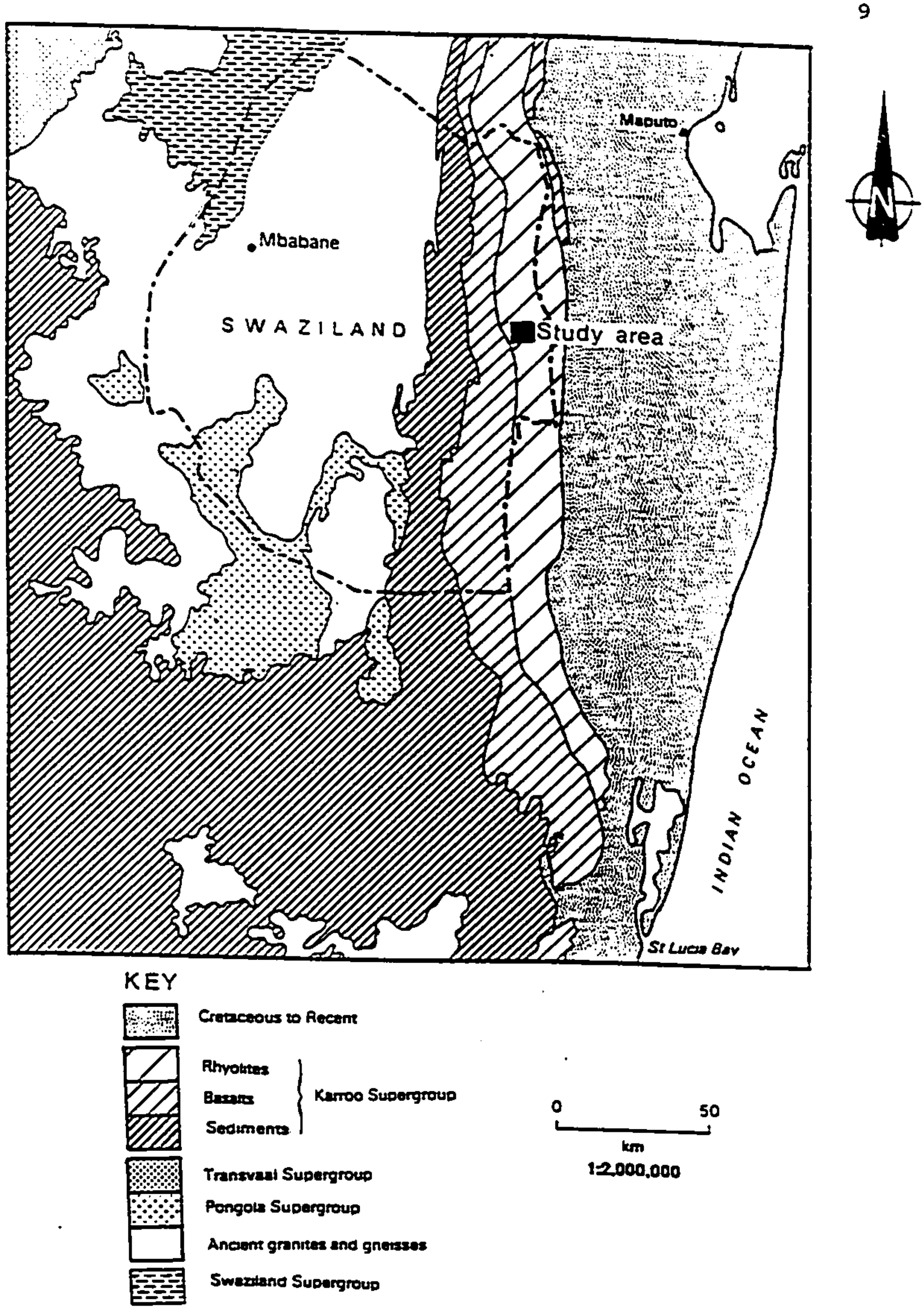

Figure 4. Simplified bedrock geology of Swaziland and adjacent areas (after Goudie and Williams, 1983).

rather than as normal ash flows, and therefore classed them as rheoignimbrites.

The whole rhyolite formation dips gently to the east, but the exact dip is unknown (Hunter,1961; Cleverly,1977). Only a few faults have been mapped in the northern part of the formation. Deep weathering occurs locally in the rhyolites.

In the study catchment, rock outcrop is less than 5%. These outcrops occur mainly on the ridge tops and in areas where gully erosion has been extensive.

2.5.2 Soil

In Swaziland, the chemical processes of soil formation are dominant as the climate is warm and there is sufficient rainfall to activate these processes. The Lubombo rhyolites weather to give acidic soils (Murdoch, 1972). The soils are described as shallow, permeable and fersiallic, formed as a result of moderate geochemical weathering.

2.6 Hydrology

The headwaters of Palata and Nunzi creeks are developed from springs and seeps. The gentle slopes tend to make the source areas swampy and the stream channels undefined until further down stream. Both Palata and Nunzi streams are perennial and drain eastwards.

In November 1988, a 90° V-Notch weir was constructed just below the Confluence of Palata and Nunzi streams (Figure 2). A rain gauge was also installed near the weir. Daily flow over the weir and daily rainfall data for the catchment are available from November 1988.

Figure 5 summarizes the streamflow hydrograph and daily precipitation at the Confluence since 1988. From this hydrograph, it is obvious that even though streamflow at the Confluence is perennial, the discharge is variable because of the strong seasonal rainfall in the area. Maximum discharge normally occurs in the summer, from October to April. Minimum flows generally occur during the winter months of May to September. Figure 5 also shows that the summer of 1991-1992 had the lowest rainfall record since rainfall monitoring began in 1988. This drought affected the whole of the southern African region.

2.7 Hydrogeology

In 1988, the Department of Geological Survey and Mines (DGSM) of Swaziland, with the assistance of the Canadian International Development Agency (CIDA) and their consultants Piteau Associates Engineering Ltd. of North Vancouver, B.C., conducted a reconnaissance groundwater survey in the Lubombo mountains. From this study it was found that groundwater flow and storage in the rhyolites occurs primarily in secondary porosity such as cracks,

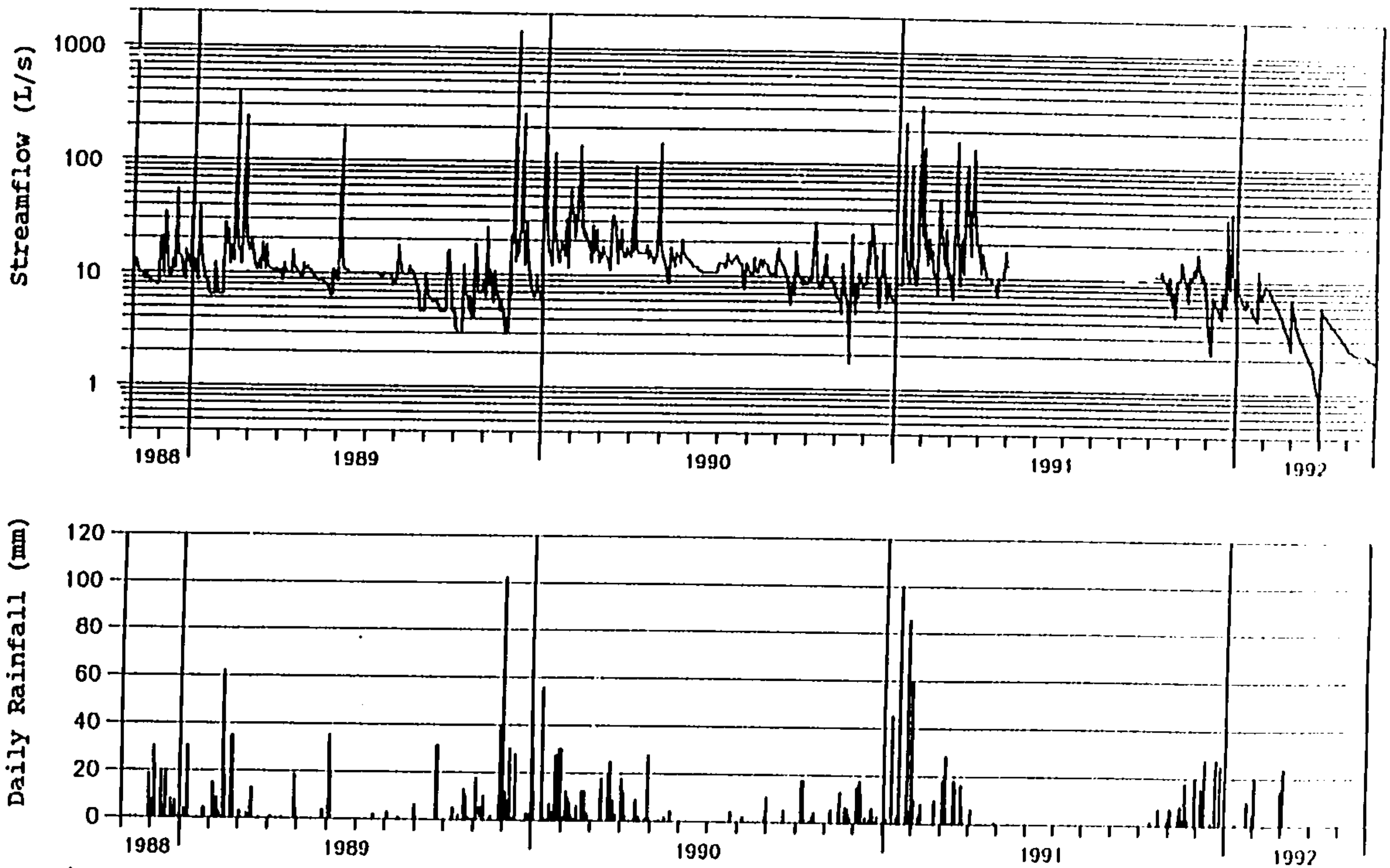

Figure 5. Streamflow hydrograph and daily precipitation at the confluence of Palata and Nunzi creeks from December 1988 to March 1992.

fissures, joints and zones of weathering (Dakin et al., 1992). In general, the bedrock is at or very close to the ground surface except in some of the valley bottoms.

2.7.1 Boreholes

Throughout the Lubombo mountains, 33 boreholes have blown yields records. Blown yield is borehole yield determined by measuring the time it takes for groundwater pushed out of the well by compressor air to fill up a container of known volume. The borehole is usually developed for sometime before the yield is measured. Eighteen of these boreholes were drilled by the Groundwater Project (DGSM-CIDA cooperative project) in 1988. Another 66 boreholes found in the area do not have any yield record.

Boreholes drilled in the massive central portion of the rhyolite flow units have very poor yields or are commonly dry. In those with water, the average yields do not exceed 0.3 L/s. However, in boreholes along lineaments that encounter fractured rhyolite bedrock, borehole yields from the fractured rhyolites ranged from 0.17 to 6.7 L/s and averaged about 2.4 L/s. One borehole drilled through weathered rhyolite produced 2.0 L/s blown yield.

Blown yields of the four shallow wells installed for this study ranged from 0.01 to 0.2 L/s.

2.7.2 Springs

Springs and seeps indicate zones of groundwater discharge. There are numerous springs and seeps throughout the Lubombo mountains. All streams from the study area originate from springs and seeps. The cumulative groundwater discharge from the local rocks sustains a modest year round flow in the streams draining the area, even during extended dry seasons.

2.7.3 Water Quality

The groundwater in the area is calcium-magnesium-bicarbonate type groundwater. In general, the quality of both the groundwater and spring water is good with low mineralization. Electrical conductivity values are commonly less than 500 μS/cm (Dakin et al., 1992). However, there are a few localities where fluoride is in excess of the 2.5 mg/L permissible limit for drinking water. Nitrate is also close to 40 mg/L in some springs and groundwater. This value is very close to the permissible limit for drinking water. The cause of these high values of nitrate and fluoride has yet to be determined.

2.7.4 Groundwater Utilization

Almost the entire population of the Lubombo region depends on springs and groundwater for water supply. Most of the water used by the rural communities comes from the large number of springs in the area. The Rural Water Supply Board has developed a few of the springs, including the EB Spring in the study area, for community use. Livestock also use spring water for drinking. Few of the boreholes have been fitted with hand pumps and windmills to provide water for domestic purposes.

3.0 REVIEW OF RUNOFF GENERATION MECHANISMS

3.1 Concepts

Freeze and Cherry (1979) described the relationship between rainfall and runoff as being the centre of hydrology. The paths followed by rainfall from the time it strikes the land surface until it appears as streamflow has been of interest to hydrologists for many decades. However, the exact mechanism in which precipitation is converted to streamflow is still not well understood.

Past studies of storm hydrology using hydrometric techniques have indicated the importance of the near-surface and surface flow paths through which storm water reaches the streams. These flow paths are a function of local climate, geology, topography, soils, vegetation, and land use (Freeze, 1974). Traditional theories used to explain storm runoff include: Hortonian overland flow (Horton,1933), partial area overland flow (Betson, 1964), variable source area saturation overland flow (Dunne and Black,1970a,b), and variable source area subsurface flow (U.S. Forest Service 1961; Hewlett and Hibbert, 1967).

Recent hydrologic studies using environmental isotopes and chemical tracers have indicated the dominance of groundwater in storm runoff in humid headwater catchments (Fritz et al.,1976; Sklash et al.,1976; Sklash and Farvolden, 1979; Pearce et al.,1986; Sklash et al.,1986; and others). Sklash and Farvolden (1979) proposed the 'groundwater ridging' hypothesis to explain the significant contribution of groundwater to storm and snowmelt runoff.

Figure 6 outlines the various mechanisms involved in the generation of storm runoff, together with studies providing field evidence for the mechanisms (Pearce et al.,1986). The research into which of these processes are important in a particular catchment is vital because the temporal changes in stream water chemistry during storm and snowmelt runoff events is controlled by how runoff is generated in a catchment (Sklash,1990).

A brief discussion of the above-mentioned storm runoff mechanisms is given in the following sections.

3.1.1 Hortonian Overland Flow

Horton (1933) produced his classical model of hillslope hydrology by assuming that the sole source of storm runoff was the excess precipitation which was unable to infiltrate the soil. This was based on the fact that soils have a finite ability to absorb water. All soils have a characteristic infiltration curve through time, with infiltration rate high at the start of wetting and falling off progressively as wetting continues, until a steady state is reached when all the soil pores become filled. If the rainfall intensity exceeds this steady state rate, excess

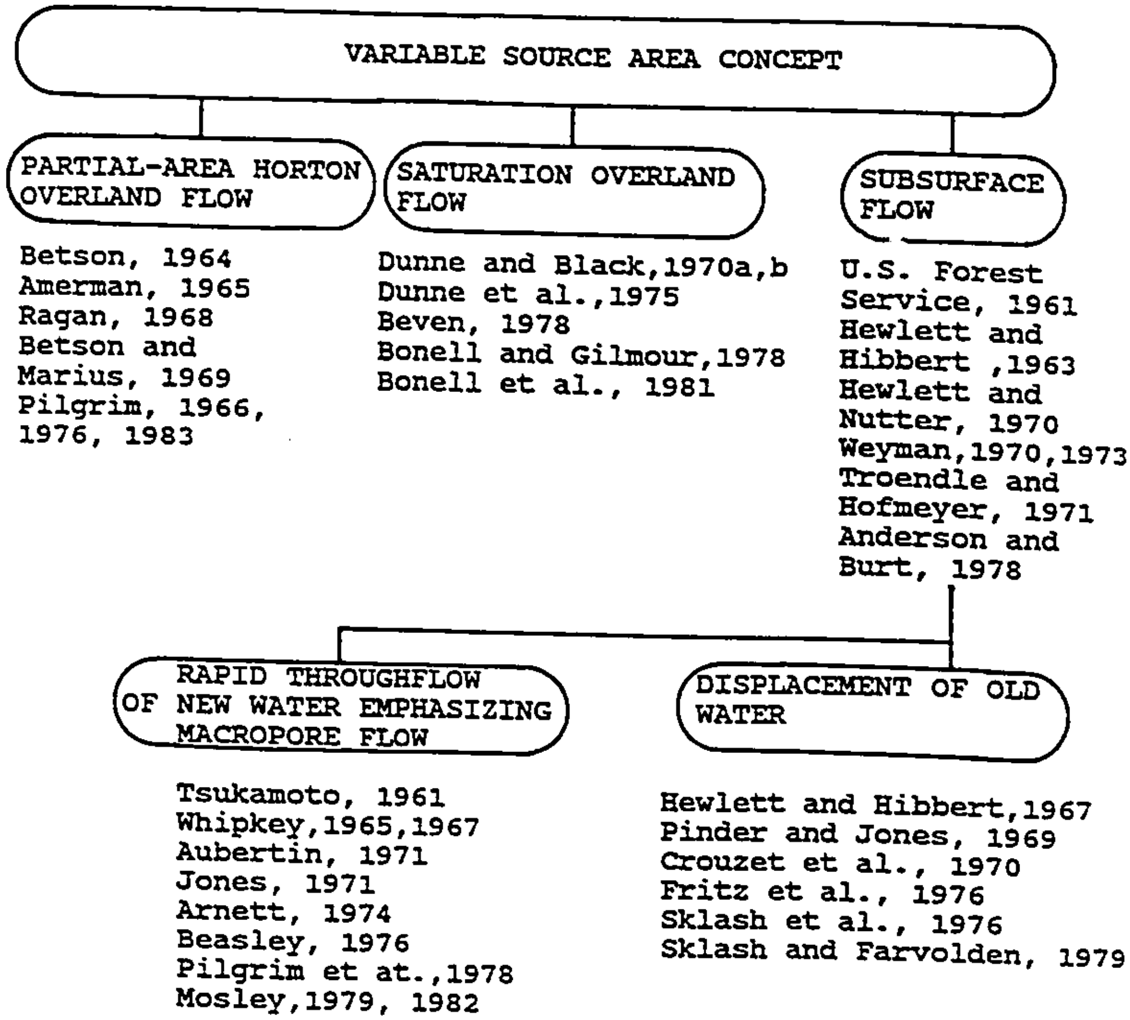

Figure 6. Some studies of the variable source area mechanisms of runoff generation (after Pearce et al., 1986).

water will pond on the surface and then flow overland to the stream.

It is suggested that the Hortonian overland flow is generated at a point on the ground surface whenever the soil at that point becomes saturated from above by infiltrating rainfall (Freeze,1974). The excess rainfall then runs overland in sheets at speeds and quantities to cause rapid rises in streams in response to storm events. Emmett (1970) confirmed the Hortonian model of overland flow by repeated field observations and detailed hydraulic study in the semi-arid regions and on agricultural lands in the midwestern United States. Emmett found that typical velocities of the Hortonian overland flow were of the order of 200 to 300 m/h.

As originally presented, Horton 's theory implied that most rainfall events exceed infiltration capacities and that overland flow is common and areally widespread. However, field studies by a number of hydrologists showed that overland flow is not widespread and rarely occurs in humid vegetated areas (Betson,1964; Ragan,1968; Dunne and Black,1970a,b; Dunne et al.,1975).

3.1.2 Partial Area Overland Flow

In the 1960 's, hydrologists working with the Tennessee Valley Authority and the U.S. Forest Service found that infiltration capacities of soils in a catchment were usually not uniform, and that production of Hortonian overland flow varied spatially. This led Betson (1964) to develop the partial area concept.

Betson (1964) examined the concept of the watershed runoff through the use of a series of mathematical models based on the integral of an infiltration capacity function. Using data from two small catchments and testing his hypothesis through multiple correlation analysis, he concluded that contributions to storm runoff originate from small, but relatively consistent, parts of the catchment. This concept is known as partial area overland flow theory (Figure 7). The contributing areas are formed as a result of saturation from above by infiltrating rainfall. Soon after detention requirements are satisfied, the excess water runs off rapidly to the stream as overland flow. The partial areas can be located anywhere in the watershed but are usually associated with soils that have shallow A horizon.

Amerman (1965), Ragan (1968), and Betson and Marius (1969) also observed the existence of partial areas from separate catchment experiments. Amerman (1965) conducted his experiment on an agricultural research catchment in Ohio. He found that the contributing areas were distributed randomly on ridge tops, on valley bottoms and on valley slopes. Ragan (1968) carried out his field study on a 619 ft long, second order stream draining a 114 acre portion of a forested catchment near Essex Centre in Vermont. His

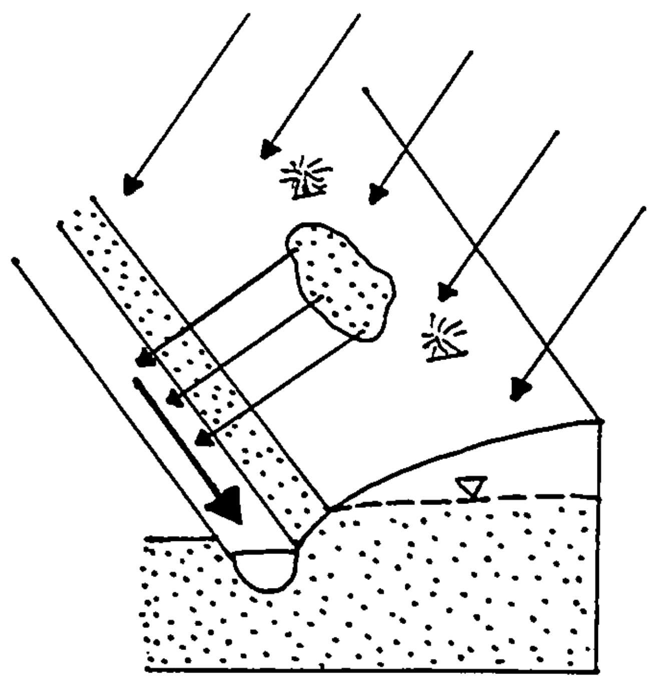

Figure 7. Partial area overland flow concept.

conclusion from the experiment also was that only a small portion of the catchment contributed flow to the storm runoff. He further observed that in a given storm event the contributing area fluctuated with changes in rainfall intensity. Pearce et al. (1986) described the partial area contribution concept as being of variable source.

The overwhelming conclusion from all the field studies is that the contributing areas are usually less than 10% of the basin, and that only about 10 to 30% of the rainfall events cause overland flow from these restricted areas.

3.1.3 Variable Source Area Saturation Overland Flow

Hydrologists working on hillslopes where soils are of high to low permeability found that infiltrating rainfall causes the water table to rise during storm events. Where the rising water table reaches the soil surface, a saturated zone forms. Rain falling on the wet areas is transmitted rapidly to the stream as overland flow. The surface emergence of the water table leads to what Dunne and Black (1970a,b) termed, "saturation overland flow". This saturation overland flow expands upslope during the storm and contracts after the rain storm (Figure 8). The expansion and contraction of the saturated overland flow due to climatic factors form the basis of the variable source area concept first described by Hewlett (1961).

Using an integrated set of surface and subsurface

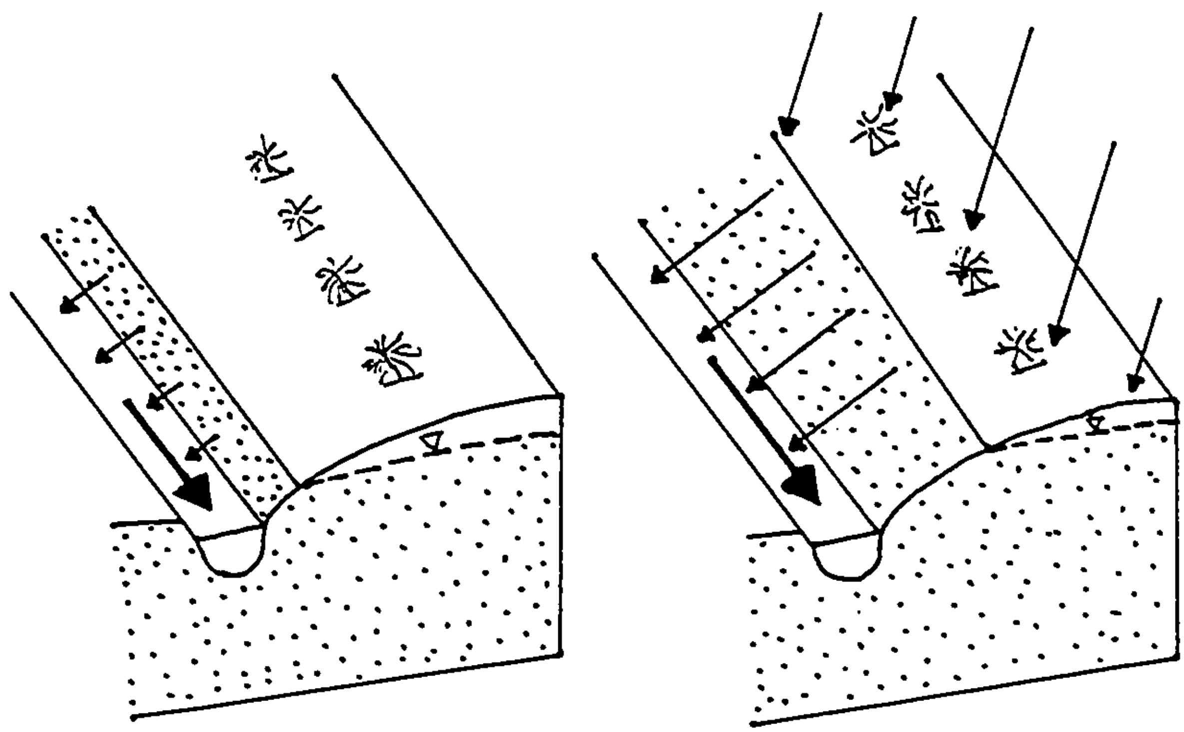

Figure 8. Variable source area saturation overland flow concept.

instrumentation on a hillslope in the Sleepers River experimental watershed in Vermont, Dunne and Black (1970a,b) were able to measure simultaneous hydrographs of overland flow, subsurface flow, and groundwater flow. They found that dominant storm flow resulted from overland flow over wetlands created by rising water tables adjacent to the stream channel. Other field studies providing evidence for the variable source area saturation overland flow were conducted in different parts of the world (e.g. Dunne et al.,1975; Beven,1978; Bonell and Gilmour,1978; Bonell et al.,1981).

In Hewlett 's (1961) original concept of the variable source areas it was implied that these would be located near the stream channels. However, later work showed that the variable source areas may occur throughout a catchment and often in locations far removed from the stream channels (Ward,1984). These soil saturated zones are linked with evidence of flow convergence governed by slopes, soil characteristics and thickness (Kirkby and Chorley, 1967).

Kirkby and Chorley (1967) suggested three probable types of location where convergence of flow might lead to surface saturation and to saturation overland flow, in addition to contiguous channel-side areas. These are: (1) hillslope hollows where flow lines converge; (2) the base of any slope, since drainage area increases downslope; and (3) areas of reduced soil moisture storage. All these areas deliver storm water to the stream by overland flow assisted by channel expansion (Engman and Rogowski,1974; Ward, 1984).

The critical difference between the partial area overland flow and the variable source area saturation overland flow is that the former generates overland flow resulting from saturation of surface soils from above, whereas the latter generates overland flow due to saturation from below by rising water table.

3.1.4 Variable Source Area Subsurface Flow

Working in the southern Appalachians in the U.S.A., where soils have an average depth of about 2 m, Hewlett (1961) and his co-workers observed no overland flow even during heavy storms. Hewlett and Hibbert (1963) built an artificial slope of homogeneous soil and recorded discharge from the slope base for many days after initial saturation. They concluded that unsaturated flow in the soil mantle of steep watersheds can contribute subsurface storm water to streams. Whipkey (1965) recorded complete storm hydrographs for subsurface flow from a natural forested slope following simulated rainstorms. This was interpreted as proof of the viability of subsurface storm flow to generate surface runoff. Similar findings were described in Britain (Weyman,1970, 1973; Anderson and Burt, 1978).

Dunne and Black (1970a,b) and others had thrown some doubt on the subsurface flow contribution to storm runoff as they considered it to be too slow to make any significant ccntribution to the storm hydrograph. The quantities measured by Hewlett and Hibbert (1963) and Whipkey (1965) were also small. Hewlett and Hibbert (1967) proposed that subsurface translatory flow or rapid displacement of stored water by infiltrating rainfall produces surface runoff.

To counter the slow rate of movement of water through the soil and weathered mantle, Hewlett and Nutter (1970) considered the channel to expand during precipitation (Figure 9). The rapidly expanding channel allows subsurface flow to reach the stream in time to contribute and sustain the upland storm hydrograph. The expansion is aided by rain falling on the wetted areas (Figure 10). As the source area network depletes, the channel shrinks back to its perennial length. The channel shrinkage is slow if the soil mantle in deep and slopes are long, and rapid if the soils are shallow and slopes are short.

Other researchers proposed that infiltrated rain water may flow rapidly to the stream through macropores (Hursh,1944; Jones,1971; DeVries and Chow,1978; Mosley,1979,1982; and others). Jones (1971) reported widespread piping in Britain and suggested that these pipes speed up throughflow to the streams during storm events. DeVries and Chow (1978) found numerous channels left behind by decayed roots in a forested mountain soil in British Columbia. They observed that infiltrated water moves more

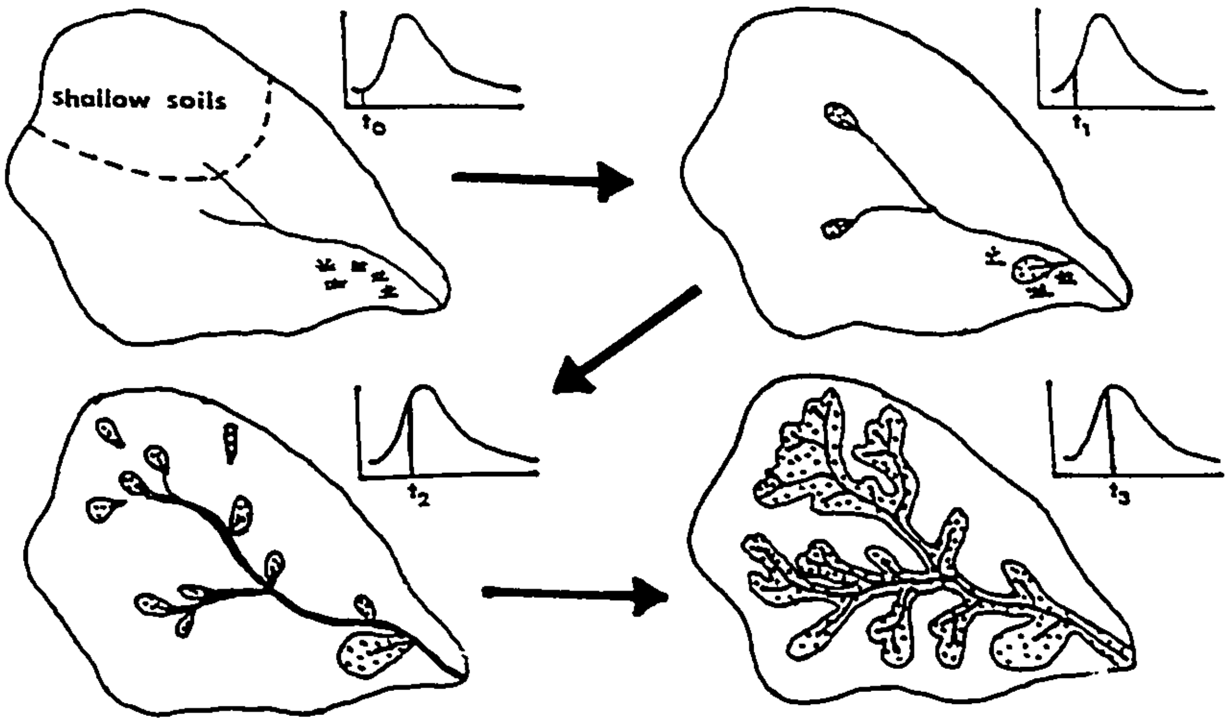

Figure 9. Expansion of the source area and channel system during a storm event (after Hewlett and Nutter, 1970).

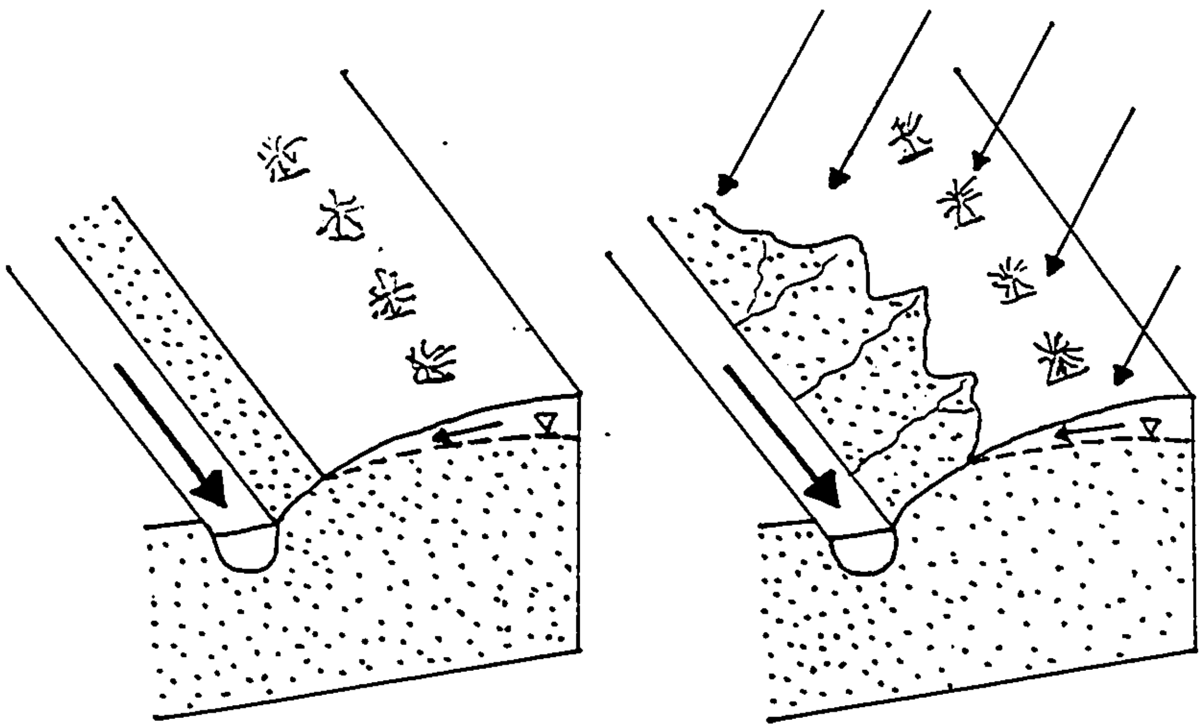

Figure 10. Variable source area subsurface flow concept.

rapidly through the channels created by the root decay than through the soil matrix.

Mosley (1979, 1982) conducted a series of experiments on the South Island of New Zealand and observed that infiltrated water moved rapidly through macropores in unsaturated soil for considerable distances at high velocities. It is also reported that in the Plynlimon experimental catchment in Britain, about 49% of streamflow passes through pipe network (Ward, 1984). Individual pipes are said to be up to 1 m in diameter and have been traced for continuous distance of more than 600 m in the catchments.

3.1.5 Channel Interception

It is suggested that in most drainage basins only between 1 and 5% of the storm water moving in the channel is derived from rain water which falls directly onto it (Selby, 1982). The reason why channel interception is considered a minor contributor to the storm flow is because of the relatively small areal extent of the stream surface in comparison with the entire catchment. However, Sklash (1978) suggested that channel interception may be important during brief storms following long periods of drought when other mechanisms are not operative.

3.1.6 Groundwater Flow

Groundwater is defined as water from the permanent saturated subsurface water flow system (Freeze, 1974). It can be discharged into the stream through near-stream springs or seeps, through the seepage face and directly into the stream bed.

Much of the streamflow generation research has not considered groundwater flow to be an important contributor to the storm runoff process (Betson, 1964; Dunne and Black, 1970a,b; Freeze, 1974; and others). For example, Freeze (1974) stated that the primary role of groundwater is to sustain baseflow during low flow periods between storms.

Many recent studies using chemical and isotopic mass balance have indicated that groundwater is an active and major contributor to storm runoff (Pinder and Jones,1979; Fritz et al.,1976; Sklash et al.,1976; Sklash and Farvolden, 1979; Pearce et al., 1986; Sklash et al.,1986; and others). Table 1 lists some of the mass balance hydrograph separation studies that show the dominance of groundwater to storm runoff.

Sklash and Farvolden (1979) postulated groundwater ridging and saturation of the capillary fringe to explain the active and significant contribution of groundwater to streamflow during storm events. According to the groundwater ridging hypothesis, the water table and the associated capillary fringe are usually close to the surface

TABLE 1. Some storm runoff studies using environmental isotopes and chemical tracers.

AUTHORS	LOCATION	AREA (km^2)	STUDY TYPE	GW. CONTRIBUTION(%) TO Total Flow	TO Peak Flow
Newbury at al., 1969	Canada	22	C		50-70
Pander and Jones, 1969	Canada	6.5,13.5	C		32-40
Visocky, 1970	U.S.A.	46	C		25
Crouzet at al., 1970	France	5.7-91	I	54-99	
Nakamura, 1971	Japan	10.3	C		25
Fritz et al., 1976	Canada	22	C, I	90	
	Canada	1.8	C, I	25-50	
Sklash et al., 1976	Canada	73-700	C, I	70	52-75
Pilgrim et al., 1979	U.S.A.	893 m^2	C	60	
Sklash and Farvolden, 1979	Canada	1	C, I		>80
	Canada	1.2, 3.9	I		65-80
Anderson and Burt, 1982	England	0.6	C	Major	
Pearce et al., 1986	New Zealand	3.8 ha	C, I		97
Sklash et al., 1986	" "	3.8ha,1.6ha, 0.3ha, 2.8	C, I	75-85	70
Turner et al., 1987	Australia	82ha	C, I	60-95	
Herrmann et al., 1987	Germany	0.76	I	89	

Explanation: GW = Groundwater
C = Chemical tracer
I = Environmental Isotope tracer

in the riparian zone adjacent to the stream. A small amount of infiltrating rain quickly converts the tension-saturated capillary fringe into phreatic water, thereby creating a groundwater ridge near the stream channel (Figure 11). The formation of the groundwater ridge rapidly increases the hydraulic gradient to the stream. If the saturated hydraulic conductivity of the soil is high, then large amount of groundwater is discharged to the stream. It is also suggested that the ridging response varies seasonally, between storms, and during storms as the water table and the capillary fringe fluctuates (Ragan,1968; Sklash and Farvolden,1979).

Groundwater ridging has been observed by other workers including: Ragan (1968), O'Brien (1980), Sklash and Wilson (1982), Gillham (1984), and Novakowski and Gillham (1988). Sklash and Farvolden (1979) proposed the groundwater ridging theory after observing quick rises in the near-stream groundwater level during storm runoff in the Hillman Creek (Ontario) catchment field experiment. They also conducted a modelling experiment by examining the groundwater response of several small hypothetical catchments using a two-dimensional, saturated-unsaturated transient finite element flow model. The formation of the groundwater ridge during one of the hypothetical watershed runs is shown in Figure 12.

Gillham (1984) carried out a simple field experiment in

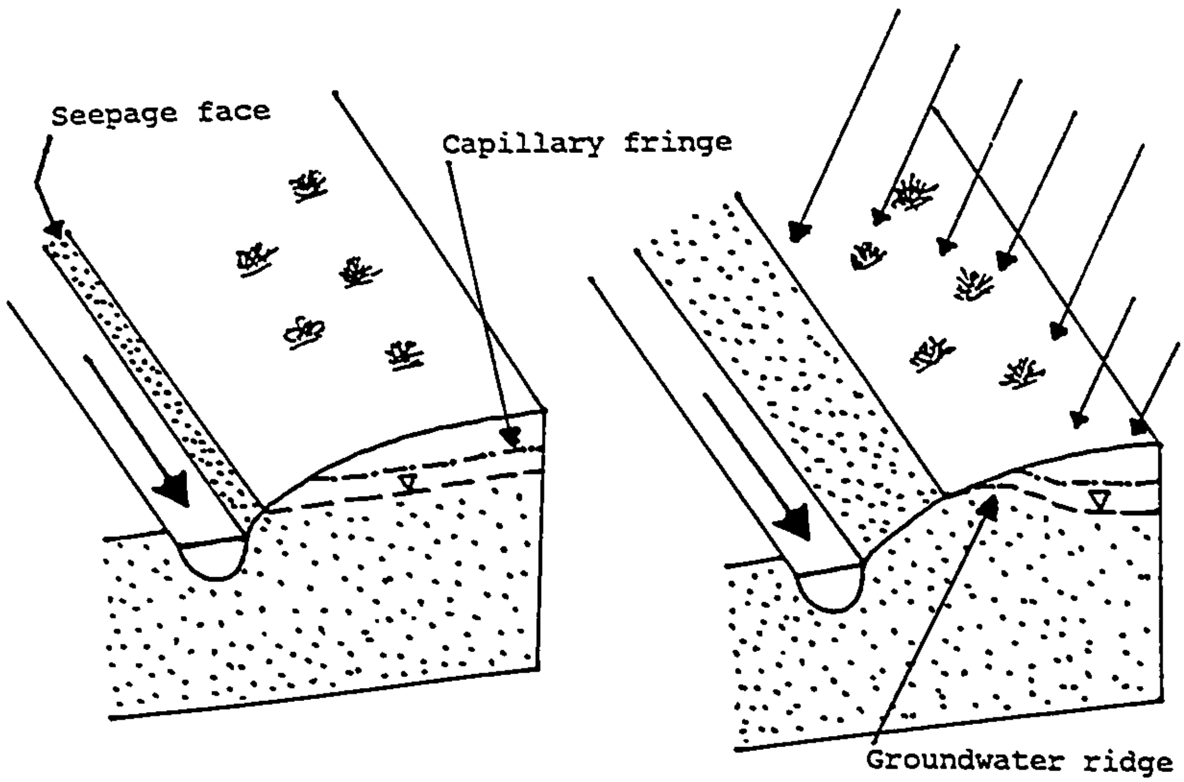

Figure 11. The groundwater ridging concept (after Sklash, 1990).

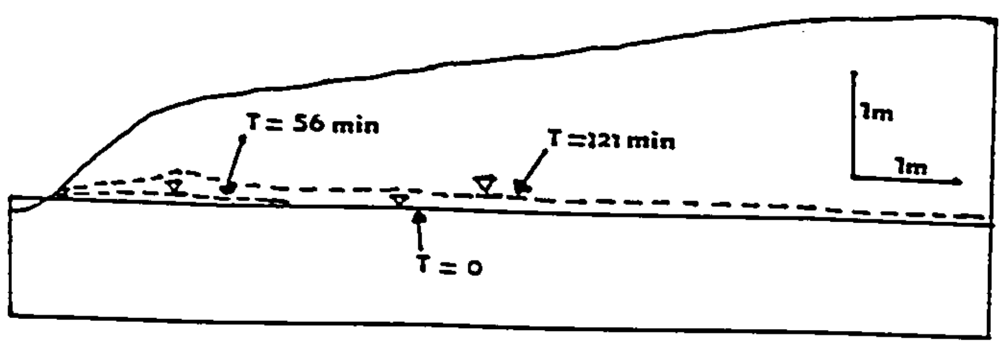

Figure 12. Formation of a groundwater ridge in a model watershed (after Sklash and Farvolden, 1979).

which the addition of 0.3 cm of water caused the water table to rise 30 cm in 15 seconds, thus demonstrating the large and highly transient influence of the capillary fringe on the position of the water table.

Laboratory and computer models by Abdul and Gillham (1984) and Stauffer and Dracos (1986) support the field evidence of groundwater ridging.

3.2 Implications of Runoff Generation Mechanisms in Study Area.

It is reported that the temporal changes in stream water chemistry during storm runoff events is controlled by how runoff is generated in a catchment (Burt, 1989; Sklash,1990). This has heightened interest in the links between storm runoff mechanisms and solute leaching.

Hall (1971) and Glover and Johnson (1974) reported significant dilution of dissolved species in the streams as a result of storm flow dominated by Hortonian overland flow. Pilgrim et al. (1979) and Trudgill et al. (1983) reported dilution of dissolved species in streams due to storm runoff dominated by subsurface macropores. Sklash and Farvolden (1979) observed increased nitrate concentrations in stream runoff during a storm event as a result of increased nitrate-enriched groundwater discharge. It is therefore important to know the storm runoff mechanism in a catchment to satisfactorly predict the quality of stream water during storm events.

Understanding of storm runoff mechanism in the Palata Creek watershed is of vital importance since acceptable water quality standards in the streams must be maintained. Since the catchment is an agricultural area, widespread use of fertilizers is common. Chemicals from the fertilizers that have not been used by the plants (such as nitrate) are transported to the streams via surface or subsurface routes during storm events. It is therefore quite important that their flow paths be clearly identified, if pollution of the streams and groundwater supplies are to be prevented.

4.0 PRINCIPLES OF ENVIRONMENTAL ISOTOPE HYDROLOGY

4.1 Definitions of Oxygen-18 and Deuterium.

Isotopes are defined as atoms whose nuclei contain the same number of protons but a different number of neutrons (Hoefs,1987). Environmental isotopes are isotopes whose natural abundance variations may be used to solve hydrogeological problems. The commonly used natural isotopes for hydrological investigations are oxygen-18 (^{18}O), deuterium (^{2}H or D), and tritium (^{3}H). In this study only ^{18}O and D were used.

^{18}O and D have global natural abundances of 0.2% and 0.15%, respectively (Ericksson, 1985). The concentrations of ^{18}O and D in a given water sample are normally measured using a mass spectrometer. ^{18}O and D concentrations in natural waters are normally expressed in delta or del (δ) notation as per mil ($^{\circ}/_{\infty}$) differences relative to the international standard, SMOW (standard mean ocean water) as defined by Craig (1961a). The del values, $\delta^{18}O$ and δD are defined by:

$$\delta^{18}O \text{ or } \delta D = (R_x - R_{SMOW})/R_{SMOW} * 1000 \qquad (1)$$

where: R is the ratio of the heavy to light isotope ($R = {}^{18}O/^{16}O$ or $R = D/H$), and x is the unkown sample. Analytical precision for $\delta^{18}O$ and δD by mass spectrometry is better than $0.2^{\circ}/_{\infty}$ and $2^{\circ}/_{\infty}$, respectively.

Both $\delta^{18}O$ and δD for SMOW are zero. If a water sample is enriched in ^{18}O and D relative to SMOW, the $\delta^{18}O$ and δD values are reported as positive. Negative $\delta^{18}O$ and δD values indicate depletion of ^{18}O and D in the water sample ralative to SMOW. Enrichment or depletion of ^{18}O and D in meteoric waters happens primarily during changes of state. Meteoric waters have negative delta values unless significantly enriched by evaporation.

4.2 Oxygen-18 and Deuterium in the Hydrologic Cycle

4.2.1 Precipitation

The various isotopic forms of water (e.g. $H_2^{16}O$, $H_2^{18}O$ and $HD^{16}O$) have slightly different vapour pressures and freezing points (Ericksson,1985). These two properties give rise to differences in ^{18}O and D concentrations in water in various parts of the hydrologic cycle. The process whereby the isotopic content of a substance changes as a result of evaporation, condensation, freezing, melting, chemical reactions, or biological processes is known as isotopic fractionation (Freeze and Cherry,1979).

The most important fractionation governing the concentrations of $H_2^{18}O$ and $HD^{16}O$ is caused by the evaporation-condensation process. $H_2^{18}O$ and $HD^{16}O$ have lower saturation vapour pressure than $H_2^{16}O$, which means that the heavy molecules are less inclined to evaporate and more inclined to condense than the lighter ones (Rodhe,1987). During evaporation, the remaining liquid is enriched in heavy isotopes and during condensation the remaining vapour is depleted in heavy isotopes.

The different behaviour of $H_2{}^{18}O$ and $HD^{16}O$, as compared to $H_2{}^{16}O$, during evaporation and condensation causes characteristic geographical and temporal patterns in the ^{18}O and D content of atmospheric water vapour and precipitation. Dansgaard (1964) and others have shown that the isotopic variations in precipitation around the world are linearly related to the mean annual temperature. The relationship is given by the following equation:

$\delta^{18}O = 0.695t - 13.6$ or $\delta D = 5.6t - 100$ ($^{\circ}/_{\infty}$) (2)

where: t is mean annual temperature in °C.

From analysis of global precipitation data Dansgaard (1964) showed that $\delta^{18}O$ values decrease with:

(i) increasing latitude (e.g. almost $-50^{\circ}/_{\infty}$ at South Pole and nearly $0^{\circ}/_{\infty}$ at the equator),

(ii) increasing altitude,

(iii) increasing distance from the oceans in the direction of vapour transport,

(iv) increasing amount of precipitation, other factors being constant.

$\delta^{18}O$ and δD values also show seasonal variations best developed in temperate latitudes. Summer values are more enriched than winter values.

Craig (1964b) reported that the ^{18}O and D concentrations in unevaporated meteoric waters are related by the following equation:

$$\delta D = 8.0\delta^{18}O + 10 \quad (^{\circ}/_{\infty}) \qquad (3)$$

This relationship is known as the Meteoric Water Line. Evaporated water can be distinguished by the fact that it contains relatively more ^{18}O than prescribed by the meteoric water line, thus plotting below this this line with a slope between 2 and 5 (Fontes,1980). Groundwater that has not undergone evaporation prior to infiltration will have $\delta^{18}O$ and δD values lying on the local meteoric water line.

4.2.2 Groundwater

^{18}O and D are frequently used as indicators of groundwater source areas and movement in the subsurface. These stable isotopes are almost ideal tracers of groundwater flow because they are constituent parts of the water molecules (e.g. $H_2{}^{18}O$ and $HD^{16}O$). Therefore they travel at the same rate and follow the same paths through the catchment as average water ($H_2{}^{16}O$) (Pearce et al., 1986; Sklash, 1990). Precipitation also applies these isotopes uniformly at no cost across the entire catchment during individual storm events.

^{18}O and D are also chemically conservative at low temperatures associated with most small catchment systems (Fritz et al., 1976; Sklash, 1990). This means that their concentrations in a volume of water do not change by reactions with the catchment materials. The concentrations of ^{18}O and D are only altered by physical processes such as mixing with pre-existing groundwater of different isotopic abundance, as well as by diffusion and dispersion.

The input functions of these tracer isotopes can be used to determine when groundwater was recharged. For example, it is generally observed that the isotopic composition of groundwater is similar to precipitation in the recharge area in temperate and humid climates (Gat, 1971). This indicates direct recharge to the aquifer. If the isotopic content of the groundwater does not change within the aquifer, it will reflect the origin of the water (Fontes, 1980). However, if the isotopic content changes along groundwater flow paths, it will reflect the history of the water. The origin deals with location, period and processes of recharge. History deals with mixing, movement and discharge processes.

4.2.3 Surface Water

During low-flow conditions which occur between storm runoff events, all the water in a stream is discharged groundwater. The chemical and isotopic character of stream water at a given location during low flow represents an integration of the upstream groundwater discharges (Sklash, 1990). During storm runoff events, rainfall is added to the stream, and may dilute the stream water if it has a different isotopic content. Details will be given in Section 5.5.1

5.0 METHODS

5.1 Physical Hydrology

5.1.1 Precipitation Measurement

Rainfall was measured in the catchment using a portable graduated plastic Tru-chek Rain Gauge made by Edwards MSG Company of Minnesota in U.S.A., and by a tipping bucket recording rain gauge, Model 2501 Rain Gauge, manufactured by SIERRA-MISCO, INC. of U.S.A. The plastic rain gauge was placed 30 cm above ground surface in an open area (Figure 2) At the end of each rainfall event, the amount of rainfall collected by the plastic rain gauge was recorded and then emptied. The time when rainfall started and stopped was also recorded. The rain gauge has an accuracy of 1%.

The tipping bucket recording rain gauge was installed together with a flow meter at the EB Spring in the catchment (Figure 2). The original plan had been to measure the rainfall and spring flow response simultaneously.

5.1.2 Streamflow Measurement.

Staff gauges were installed at Palata and Nunzi streams and at their confluence (Figure 2). The river stages were observed and recorded daily and more frequently during storm events. A Stevens Type F Recorder Model 68 was installed at Palata stream to measure continuous river stage changes. Daily flow of the protected EB Spring was also measured manually using a gate valve.

5.2 Physical Hydrogeology

5.2.1 Drilling Methods

Four shallow wells, M1 through M4, were drilled close to the EB Spring (Figure 2) using the direct rotary method. The wells were drilled by the Department of Geological Survey and Mines of Swaziland for this study. The wells were drilled with a 152 mm outside-diameter tricone bit. Air and water were used as drilling fluids to bring rock cuttings to the surface and also to cool the bit. Each borehole was drilled to the base of weathered bedrock at 20 m below ground surface. Three of the wells, M1 through M3, were drilled in a line from the spring upslope. The first well, M1 is 5 m from the spring, M2 and M3 are 50 m and 150 m from the spring, respectively (Figure 2).

Two other wells, D1 and D2 were driven by hammering to depths of 1.5 m and 1 m, respectively, very close to Palata Creek (Figure 2). Well D1 is in the Palata streambed and D2 is 34 m away upslope and perpendicular to the stream. Each well is 65 mm in diameter.

5.2.2 Well Installation

The four shallow wells, M1 through M4, were each completed with a multilevel piezometer nest consisting of three piezometers (Figure 13). The piezometers were

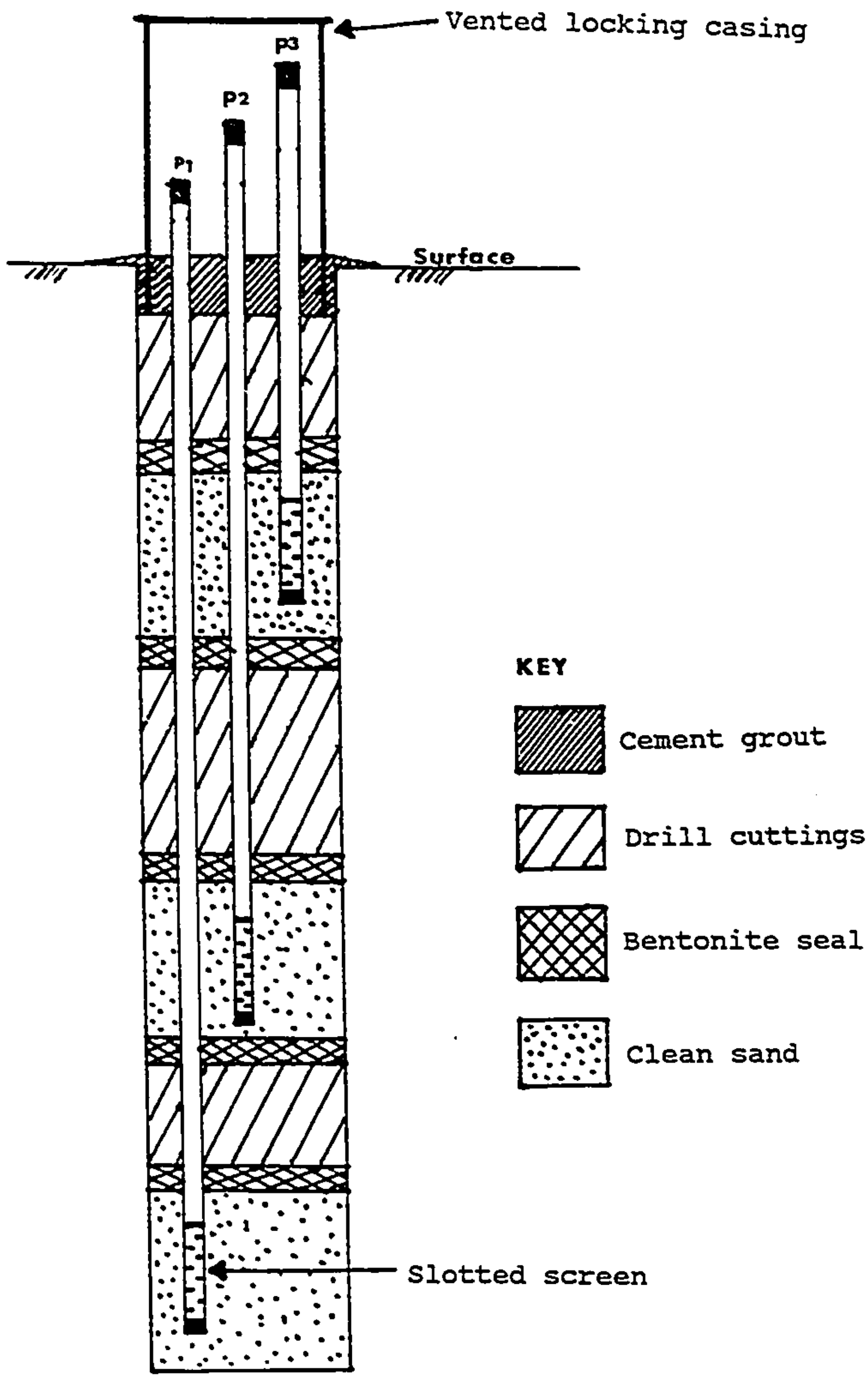

Figure 13. Typical piezometer nest completion in the monitoring wells M1 through M4.

installed to characterize the groundwater quality at various depths and to evaluate groundwater hydraulics. All the piezometers are 19 mm diameter PVC pipes with 1 m long slotted screens. In all the wells, the deepest piezometer, P1 was placed at depth of 18.5 m, and P2 and P3 were installed at depths of 10 m and 6 m, respectively.

Clean medium-grained river sand was placed around each screen to keep away fine materials. A 30 cm bentonite clay was used as a seal to isolate each screen and also to prevent downward water leakage. At the surface, a concrete apron was emplaced to prevent ponding of surface water. A vented locking casing was placed at the top of each well to protect against accidental damage and vandalism.

The driven wells, D1 and D2, were each completed with two piezometers with 10 cm long slotted screens. In D1, the deepest piezometer, P1 was open at 1.3 m below ground surface, and P2 at a depth of 0.5 m. Clean river sand was used around the screens. Bentonite seal was used to separate each screen and to prevent downward water leakage. In Well D2, the deepest piezometer P1 was opened at 0.8 m and P2 at 0.5 m.

5.2.3 Water Level Measurements

In all the wells, water levels were measured daily and more frequently during storm events, using an electric contact gauge. The electric contact gauge was a Seba KLL electric flat tape sounder, graduated in centimetres. A pressure transducer was also used to measure water level in the shallowest piezometer P3 in well M1 near EB Spring. All water level measurements were corrected to ground level by subtracting the casing stick up.

5.2.4 Measurement of Hydraulic Conductivity

To determine values of hydraulic conductivity (K) of the formation at each piezometer depth, single well tests were conducted using the bail test method (Freeze and Cherry, 1979). The bail test is conducted by instantaneous reduction of head in the piezometer by removing a known volume of water. Increasing head against time is then observed.

Data analysis for determining the K values was carried out using the Hvorslev (1951) method. In this method the hydraulic conductivity, K is given by the following equation:

$$K = r^2 \ln (L/R)/2LT_o \qquad (4)$$

where: K is the hydraulic conductivity, r is radius of piezometer casing, R is radius of screen, L is length of screen, and T_o is the "basic time lag", that is, the time for full recovery at initial inflow rate.

5.2.5 Soil Moisture Collection

Direct measurement of subsurface flow during rain storms was attempted by constructing a 2 m deep pit on a 7° slope in the catchment (Figure 2). Three collection troughs constructed from cafeteria trays were inserted in the upslope wall of the pit (Figure 14). The uppermost trougn was inserted at the base of the organic rich soil which contained numerous roots and some macropores. The second trough was installed at the base of a silty clay soil which contained weathered rock fragments and occasional plant roots. The lowermost trough was inserted in the middle of a homogeneous silty clay soil.

A clean sand filter was placed at the top of each trough to keep away fine material. Bottles to collect the water from the troughs were placed at the bottom of the pit and buried. The pit with the troughs was backfilled. The top of the pit was covered with plastic to prevent rainfall from infiltrating through the backfill. Collected water was brought to the surface by using a vacuum pump.

5.2.6 Soil Analysis

Soil samples at each trough depth were taken for analysis of grain size distribution at the Agricultural Research Station in Swaziland. The grain-size distribution of the soil samples was determined by mechanical sieve and hydrometer analyses. Soil samples with particles greater than 0.02 mm were analyzed by sieving, and smaller particles by hydrometry which involved measuring rates of settlement

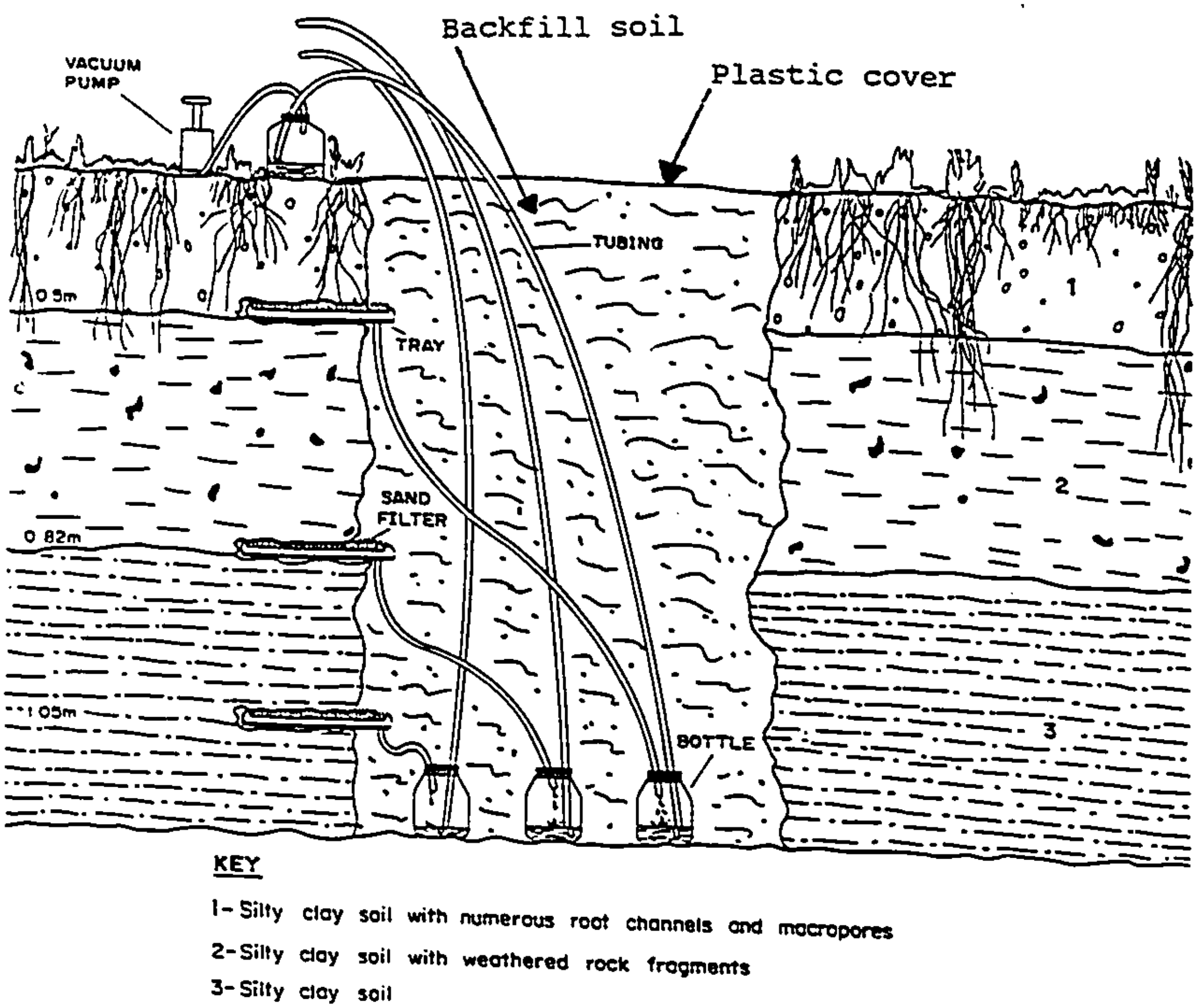

Figure 14. Throughflow collector system.

in suspension. The soil samples were also analyzed for pH and organic matter.

5.3 Isotope Hydrogeology

5.3.1 Sample collection

Low flow stream samples were collected weekly at Palata, Nunzi and the Confluence of the two streams (Figure 2). A Cygnus Automatic Liquid Sampler was installed at EB Spring. During storm events more frequent sampling was conducted. Bulk rain samples for each storm event were also collected.

The shallow well D1 at Palata streambed was sampled regularly during storm events and at low flow. The other boreholes were sampled once during the study period. The wells were purged before sampling. All samples were collected in 50 mL plastic bottles which were filled and tightly sealed with no space at the top. In all, 85 water samples were collected.

5.3.2 Sample Analysis

All collected water samples were analyzed for ^{18}O. In all 81 samples were collected. Selected water samples were analyzed for D.

The ^{18}O samples were prepared by the carbon dioxide (CO_2) gas equilibration technique as described by Epstein and Mayeda (1953) at the University of Windsor Stable

Isotope Extraction Laboratory. A distilled water standard with a known $\delta^{18}O$ value was run with each group of ten samples as a check for laboratory quality control. The ^{18}O isotopic analyses were completed at the Ottawa-Carleton Geoscience Centre Stable Isotope Facility, using a SIRA-12 Mass Spectrometer. The instrument measures the mass of CO_2 molecules in the CO_2 gas in equilibrium with the liquid water sample. Obtained $^{18}O/^{16}O$ ratio of the sample was compared to a reference water with a known $\delta^{18}O$-value as compared to SMOW. The accuracy of the $\delta^{18}O$-values of the samples is $0.2°/_{\infty}$.

Deuterium isotopic analyses were conducted at the Environmental Isotope Laboratory, University of Waterloo, Canada. The samples were analyzed with a Micromass Model 903 mass spectrometer. The accuracy of the δD-values of the samples is $2°/_{\infty}$.

5.4 Chemical Analysis Methods

Water samples for chemical analysis were collected in 1 L plastic bottles at the same locations and times with those of isotope analysis. The water samples were analyzed for pH, electrical conductivity, nitrate, fluoride and chloride.

Electrical conductivity (EC) and pH were measured in the field immediately after sample collection using a portable HI8733 Conductivity Meter and an HI8314 Membrane pH

Meter, respectively. Both instruments are from Hanna Instruments. The instruments automatically correct readings to 25 °C standard temperature. Temperature for each water sample was also measured in the field when the sample was taken.

Chloride (Cl), nitrate (NO_3) and fluoride (F) in the water samples were determined at the Geological Survey and Mines Department, Chemistry Laboratory, Swaziland. The water samples were preserved by refrigeration prior to analysis. The methods used in the analyses are those adopted from the Standard Methods for the Examination of Water and Wastewater, by the American Public Health Association (1976).

Chloride concentrations in the water samples were measured by the argentometric titration method. Nitrate in the water samples was tested using the Hach Nitraver 5 Nitrate Reagent Powder Pillow method, and fluoride was determined using a 407A Specific Ion Meter. With each batch of samples analyzed, control standards were included to check precision on the determination. The error in the analysis is about 5%.

5.5 Hydrograph Separation

5.5.1 Mass Balance-Isotope Method

The environmental isotope tracer technique of hydrograph separation estimates groundwater (old water) and rain water (new water) components of a runoff event by solving the steady state mass balance equations for the water and tracer fluxes in the stream (Sklash, 1990). These equations simplify to the following form:

$$Q_o = (C_s - C_n)/(C_o - C_n) * Q_s \tag{5}$$

$$Q_n = Q_s - Q_o \tag{6}$$

where: "Q" is discharge, "C" is tracer concentration, "s" is the stream, "o" is the old water, and "n" is the new water. 'New water' is water from the current rain event. 'Old water' is subsurface water that existed in the catchment prior to the current rain event. It include groundwater, baseflow and soil water. The use of equations (5) and (6) requires that the old and new water have distinct isotopic signatures and that the new water maintain a constant isotopic content (Sklash and Farvolden, 1979). This method of hydrograph separation works because the new water usually dilutes the old water during storm events, and the old water usually has a constant tracer concentration.

^{18}O is the environmental isotope tracer used in this study to separate the hydrographs into old water and new water. Baseflow samples were used to characterize the isotopic content of the old water since it represented an integrated isotopic concentration from the catchment. Baseflow was also easy to sample.

Since the streams were not amenable to constructing a stage-discharge relationship except at the weir, the contributions of the old and new water at the Palata and Nunzi monitoring stations are expressed as percentages of the total discharge.

5.5.2 Mass Balance-Chemical Tracer Method

The natural chemical tracers considered in this study are electrical conductivity (EC) and chloride (Cl). These can be inserted into the steady state mass balance equations (5) and (6) to estimate percentages of old and new water in the streams during storm events. The use of chemical tracers in hydrograph separation is based on the general observation that old water has higher concentrations of most chemical parameters than new water.

The shortcomings of separating storm hydrographs on the basis of chemical parameters is that most chemical parameters are not conservative. It has been found that the chemistry of the new water varies both areally and temporally as the rain water interacts with the catchment materials on the way to the stream (Nakamura,1971; Pilgrim et al.,1979). In general there is an increase of concentration of dissolved solids with increasing time of contact of water with the soil. The second complication is that solutes are flushed from the soil surface during the early part of storms that occur after prolonged period of no storm runoff (Pilgrim et al.,1979; Sklash et al.,1986). These complications may lead to over-estimation of the groundwater contribution during the mass balance hydrograph separation.

5.5.3 Mass Balance-Temperature Method

During each storm event the temperature of the baseflow was different from that of the rainfall. The temperature values can be were inserted in the mass balance equations (5) and (6) to determine the relative contributions of the old and new water in the streams during storm runoff.

5.5.4 Groundwater Stage-Groundwater Discharge Method

The main hydrometric technique in this study involved the establishment of a groundwater stage-groundwater discharge rating curve for the hydrograph separation (Sklash and Farvolden, 1979). This was accomplished by plotting baseflow stage of Palata stream against groundwater stage from two shallow monitoring wells in the Palata streambed.

By monitoring groundwater stage during runoff events, groundwater contribution was estimated by referring to the groundwater stage-groundwater discharge rating curve. The groundwater contribution for each storm event is given in percentage of total discharge.

6.0 RESULTS AND DISCUSSION

6.1 Hydrogeology

6.1.1 Geology

The bedrock in the study area is a massive, fine-grained light grey rhyolite with white and pink feldspars. It outcrops mainly on the ridge tops and in areas where soil erosion has been extensive. The bedrock is locally weathered. About 10 m of weathered bedrock were encountered during drilling of the shallow wells M1 through M4 (Figure 15). Well logs are given in Appendix A.

6.1.2 Soils

Some physical and chemical properties of the soils in the catchment are shown in Table 2. The soils are generally brown to reddish brown in colour and sandy to silty clay in texture. According to the soil textural classification chart (Soil Conservation Service, 1951), the soil is classified as clay. Soil thickness is variable in the catchment. Near the ridge tops, the soil consists only of thin layer of organic material resting directly on the bedrock. On the valley slopes and in valley bottoms, and where relatively little recent erosion has occurred, the soil may extend to a depth of 5 m or more (Figure 15).

Where the soil is well developed, the upper 50 cm of the soil usually contains numerous plant roots with occasional macropores resulting from decayed plant roots.

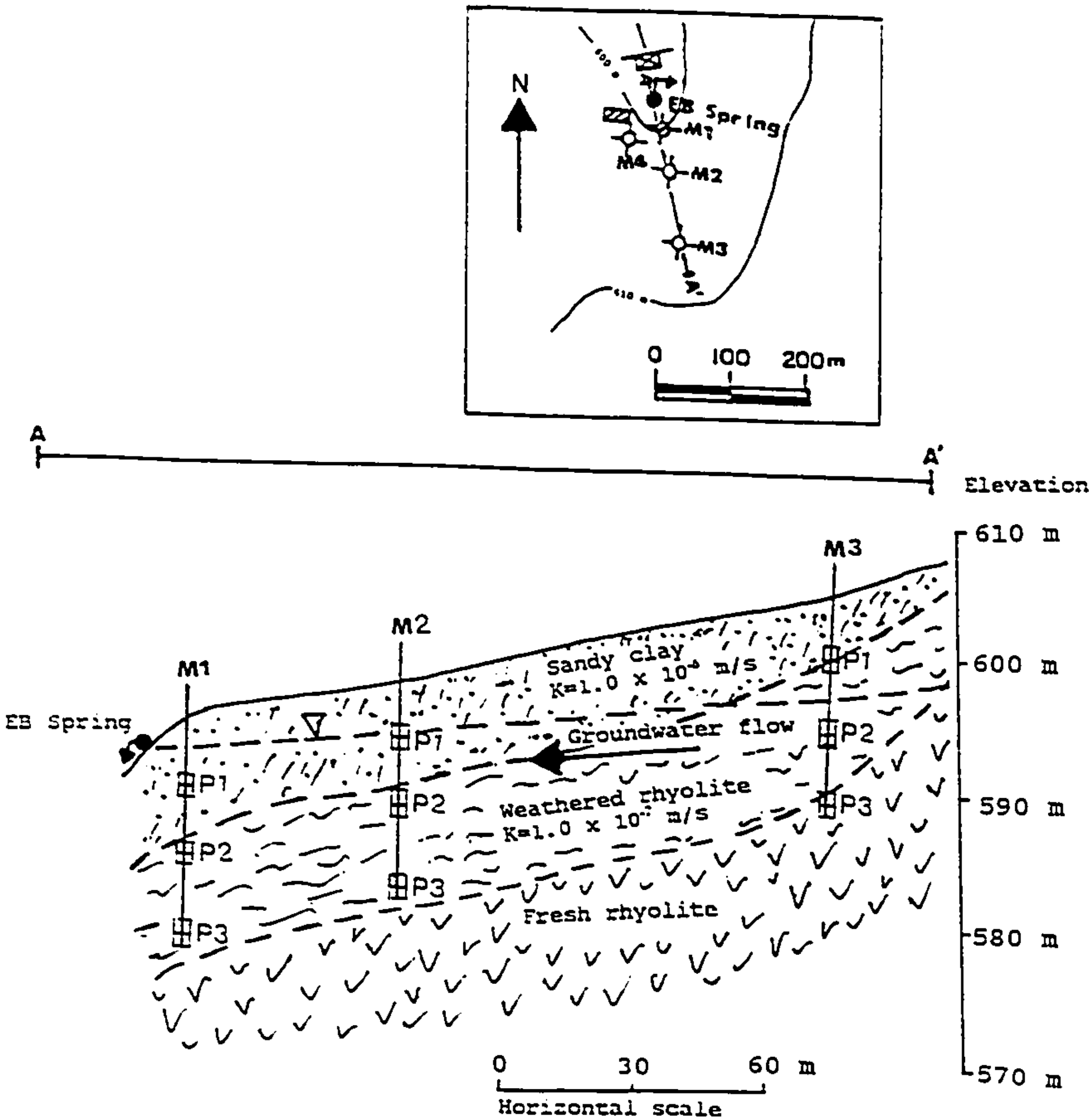

Figure 15. A cross section from M1 through M3.

TABLE 2. Some physical and chemical properties of the soil collected at the throughflow collector site.

Soil depth (cm)	Particle-size distribution (%) Sand (0.2-2mm)	Silt (0.2-0.002mm)	Clay (<0.002mm)	Textural Class	Organic matter(%)	pH
0-50	30	15	55	Clay	2.6	5.3
50-82	23	17	60	Clay	1.6	5.3
82-105	42	16	42	Clay	0.3	5.3

Observed macropores are up to 1 cm in diameter. Below a depth of 50 cm, the soil contains weathered rock fragments and isolated plant roots which decrease in frequency with depth. The sand content of the soil increases with depth.

Organic content of the soil varies from 2.6% in weight in the upper 50 cm to about 0.3% at depth. The soil is acidic with and average pH of 5.3. The acidity of the soil is probably derived from the parent rock which is comprised mostly of acid volcanic rocks.

Rainfall infiltration is fairly rapid where the soil is well developed. A simulated rainstorm at the throughflow collection pit applied 60 mm/h of water using a garden spray. Infiltration reached the collector at 50 cm in less than 2 hours. The simulated rainstorm was targeted upslope but very close to the throughflow collecting troughs (Figure 14).

There was no overland flow observed during the rainstorm simulation. Plant roots and the macropores probably improve infiltration. Some of the macropores may be capable of providing lateral flow of subsurface water from the hillslopes to the streams during heavy storm events. However, since there was little rain during the study period, no subsurface water accumulated in the throughflow collecting pit as a result of the rainstorms.

6.1.3 Hydraulic Conductivities

Hydraulic conductivity (K) values calculated from the Hvorslev (1951) method for the soil and weathered rhyolite are listed in Table 3. Appendix B gives the bail test data for the various piezometers.

The soil has an average hydraulic conductivity of 1.0 x 10^{-6} m/s. This value is the geometric mean of five K values for the soil from the various wells (Table 3). The hydraulic conductivity of the soil is typical of a clay soil with significant sand and silt (Todd, 1980). The slight increase of the hydraulic conductivity of the soil with depth is probably due to increased sand content with depth (Table 3).

The average hydraulic conductivity of the weathered bedrock is 1.0 x 10^{-7} m/s. This value is an order of magnitude smaller than the soil value. One would expect a further decrease of hydraulic conductivity in the massive unweathered rhyolite.

6.1.4 Hydraulic Heads and Gradients

In wells M1 through M4 (Figure 2), the hydraulic heads remained constant throughout the study period probably because there was not enough rain to recharge the groundwater. Another possibility is that a zone of high permeability was discharging groundwater in this locality and thus keeping the heads constant even during the extended

TABLE 3. Hydraulic conductivities of the soil and weathered rhyolite.

Well	Piezometer	Formation	Hydraulic Conductivity (m/s)
M1	P1	Weathered rhyolite	1.0×10^{-7}
	P2	Weathered rhyolite	2.0×10^{-7}
	P3	Soil	1.6×10^{-6}
M2	P1	Weathered rhyolite	0.93×10^{-7}
	P2	Weathered rhyolite	1.0×10^{-7}
	P3	Soil	No data
M3	P1	Weathered rhyolite	0.81×10^{-7}
	P2	Weathered rhyolite	0.81×10^{-7}
	P3	Soil	No data
M4	P1	Weathered rhyolite	1.1×10^{-6}
	P2	Soil	1.9×10^{-6}
	P3	Soil	0.5×10^{-6}
D1	P1	Soil	1.4×10^{-6}
	P2	Soil	0.5×10^{-6}

Piezometer intake above water table where No data drought. The water level is topographically controlled. It varied from a depth of about 10 m in upslope M3, to a depth of about 3.5 m below land surface downslope in M1 (Figure 15).

Using wells M1, M2 and M4, the horizontal hydraulic gradient and groundwater flow direction were calculated. The horizontal hydraulic gradient is about 0.033. The vertical hydraulic gradient varied slightly from well to well, and the average is about 0.05 in the downward direction. The groundwater flow direction conforms with the surface topography, that is, flowing from the surface divide downslope to the topographically convergent area represented by the EB Spring in this particular locality (Figure 15). Groundwater flow is likely to be topographically controlled in other sections of the catchment as well, unless there are major fractures in the bedrock.

Figure 16 shows the stage hydrographs of the Palata Creek and groundwater in piezometers P1 and P2 installed in the driven well D1 in the Palata streambed. Piezometers P1 and P2 are opened at depths of 1.3 m and 0.5 m, respectively below the streambed. The vertical hydraulic gradient is upward. During baseflow periods, the vertical hydraulic gradients calculated from P1 and P2 are about 0.025. It was observed that the near-stream heads at P1 and P2 responded very rapidly following the onset of rain events (Figure 16).

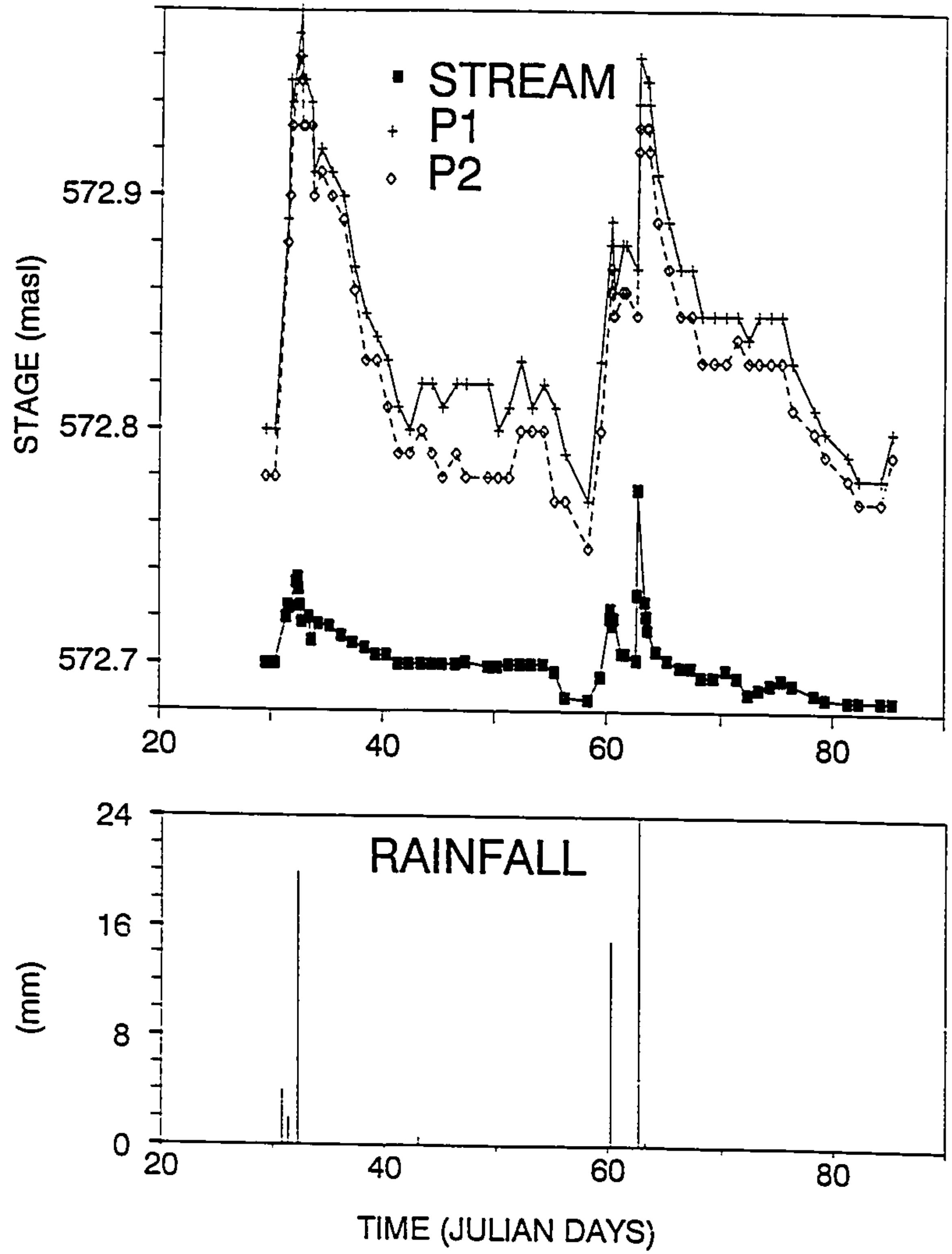

Figure 16. Stage hydrographs of Palata Creek and piezometers P1 and P2 in well D1 (Day 1 = January 1, 1992).

The hydraulic gradient to the stream increased to about 0.04 during the storm events and the the stream remained effluent during all events.

The intake of piezometers P1 and P2 in well D2 lie above the water table. Well D2 is located 34 m away from Palata. During each storm event, water level quickly reached P1 and gradually subsided after the event. The water level usually reached P1 in D2 after the heads at P1 and P2 in well D1 had reached maximum height.

6.1.5 Isotopes

The δD and $\delta^{18}O$ values for selected waters in the catchment are given in Table 4, and are plotted in Figure 18. The water samples were collected from groundwater, baseflow, rain and storm runoff, and are the only ones for which both δD and $\delta^{18}O$ were determined. The $\delta^{18}O$ data for all the samples are included in Appendix C. The global metecric water line (GMWL) of Craig (1961b) and the Swaziland meteoric water line (SMWL) determined by Dakin et al. (1992) are also shown in Figure 17.

The groundwater and baseflow values cluster around the isotopically light corner of the diagram, in a range of δD -23.46 ‰ and $\delta^{18}O$ -4.19 ‰ to δD -16.85 ‰ and $\delta^{18}O$ -3.49 ‰. Most of the baseflow and groundwater samples lie on or below the GMWL. The position of the groundwater data in relation to the GMWL indicates that the groundwater

TABLE 4. δD and $\delta^{18}O$ values for selected waters of the catchment.

Date	Sample source	Type	δD (°/∞)	$\delta^{18}O$ (°/∞)
01/2/92	Event 1	Rain	-9.44	-2.44
29/2/92	Event 2	Rain	-10.16	-2.81
02/3/92	Event 3	Rain	-13.34	-3.71
20/2/92	Groundwater (M4)	P1	-19.55	-3.73
"	"	P2	-19.54	no data
"	"	P3	-23.37	-3.80
30/1/92	Groundwater (D1)	P1	-21.94	-3.80
"	"	P2	-19.51	-3.65
30/1/92	Palata	Baseflow	-23.30	-3.65
30/1/92	Nunzi	Baseflow	-16.85	-3.49
30/1/92	Confluence	Baseflow	-20.46	-3.55
30/1/92	EB Spring	Baseflow	-23.46	-4.19
01/2/92	Palata	Stormflow	-15.76	-3.55
"	Nunzi	Stormflow	-13.66	-3.34
"	Confluence	Stormflow	-18.80	-3.40

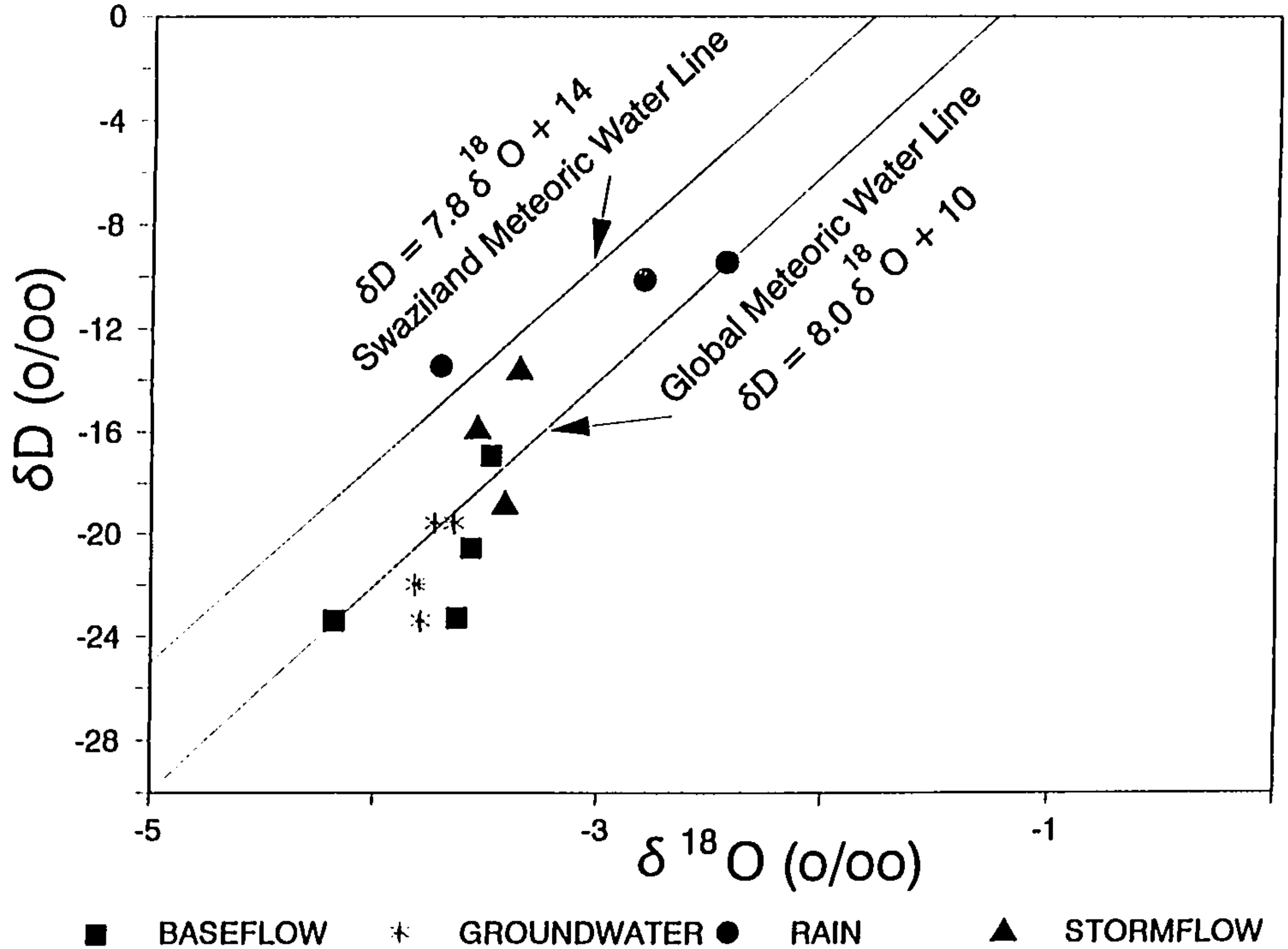

Figure 17. δD versus $\delta^{18}O$ for selected waters in the catchment.

was recharged by infiltrating rain that did not undergo extensive evaporation.

The $\delta^{18}O$ values of the three storm events varied from -2.44 to -3.71 °/$_{\infty}$, and their δD values ranged from -9.44 to -13.34 °/$_{\infty}$. The first rainfall event occurred on Day 32 (Day 32 is February 1 in Julian Days, Day 1 is January 1, 1992), and it had a $\delta^{18}O$ value of -2.44 °/$_{\infty}$ and a δD value of -9.44 °/$_{\infty}$. This rain sample plots on the GMWL, and the other rainfall results plot above the line (Figure 17). Dakin et al. (1992) also found that most rain in Swaziland plots above the GMWL.

Low flow $\delta^{18}O$ values for Palata, Nunzi, Confluence and EB Spring are listed in Table 5. Table 6 shows the groundwater $\delta^{18}O$ values. The groundwater and baseflow values are similar to those found by Dakin et at. (1992) in the area. Groundwater $\delta^{18}O$ values ranged between -3.69 to -3.94 °/$_{\infty}$, with an overall average of -3.84 °/$_{\infty}$ and standard deviation of 0.09. Baseflow at all the sampling points was slightly enriched in $\delta^{18}O$ relative to the groundwater. For example, baseflow at the sampling point at Palata was enriched by 0.02 °/$_{\infty}$ relative to the groundwater. Nunzi and Confluence were enriched by 0.36 °/$_{\infty}$ and 0.30 °/$_{\infty}$, respectively, relative to the groundwater in Palata.

The slight enrichment in the baseflow is probably due to kinetic fractionation processes occurring during evaporation in the surface waters of the streams. Palata

TABLE 5. Baseflow $\delta^{18}O$ in the streams.

Stream	$\delta^{18}O$ (°/∞) No. of sample	Average value (°/∞)	Standard deviation
Palata	6	-3.82	0.09
Nunzi	6	-3.48	0.04
Confluence	6	-3.54	0.05
EB Spring	5	-4.08	0.09

TABLE 6. $\delta^{18}O$ in groundwater

Well	Piezometer	Depth (m)	$\delta^{18}O$ (°/∞)
M1	P1	18.5	-3.94
	P2	10.0	-3.75
	P3	5.5	no data
M2	P1	18.5	-3.69
	P2	10.0	-3.89
M3	P1	18.5	-3.89
	P2	10.0	no data
M4	P1	18.5	-3.73
	P2	10.5	no data
	P3	6.5	-3.89
D1	P1	1.3	-3.87

Creek may appear less evaporated since it was sampled close to the headwaters of the stream (Figure 2). Nunzi and the Confluence were sampled further downstream in the catchment, and consequently they appear more evaporated when sampled.

Groundwater in wells M1 through M4 was not recharged by the rain storms that occurred in the catchment during this study. The water levels in these wells remained static throughout the study period. However, water levels in wells D1 and D2 located close to Palata stream responded very rapidly during the onset of rain storm events (Figure 16). The average prestorm $\delta^{18}O$ value for the groundwater in well D1 was -3.87 $^{\circ}/_{\infty}$. During storm events, the isotopic content of water in the well changed gradually to an average value of -3.65 $^{\circ}/_{\infty}$. From these observations it can be deduced that areas close to the stream channels are recharged readily following storm events. The recharge in the rest of the catchment is probably sporadic and subject to individual periods of high rainfall.

Vogel et al. (1963) and Vogel and Van Urk (1975) reported that in most parts of South Africa and Namibia there was a consistent difference between the isotopic content of groundwater and that of average precipitation. They found that groundwater in general is depleted in heavy isotopes relative to precipitation in recharge areas. They also reported that the isotopic composition of groundwater corresponded to the isotopic composition of exceptionally heavy rainfall. This was interpreted to mean that recharge does not occur continuously and regularly in the region, but is confined to periods of very heavy rainfall when precipitation tends to be depleted in the heavy isotopic content. Groundwater recharge in this catchment probably occurs under similar conditions as in South Africa and Namibia, except along the riparian areas of the streams.

The isotopic composition of the EB Spring and two other springs sampled by Dakin et al. (1992) close to the study area plot on the GMWL. These springs also have the lightest isotopic composition among the waters of the catchment. Therefore, the isotopic composition of the springs is probably close to the composition of the local rain at the time of infiltration.

Figures 18, 19 and 20 summarize the temporal variations in $\delta^{18}O$, Cl and EC in Palata, Nunzi and Confluence, respecively during this study. The baseflow $\delta^{18}O$ values in the streams remained fairly constant throughout the study period despite rain storms with differing isotopic contents.

Storm Event 1, which occurred on Day 32, had a $\delta^{18}O$ value of -2.44 $^{o}/_{oo}$. Event 2 occurred on Day 60 and had a $\delta^{18}O$ value of -2.81 $^{o}/_{oo}$. The last storm event during the study occurred on Day 62 and had a $\delta^{18}O$ value of -3.71 $^{o}/_{oo}$. The isotopic composition of streamflow responded to individual rainfall events by increasing during storm

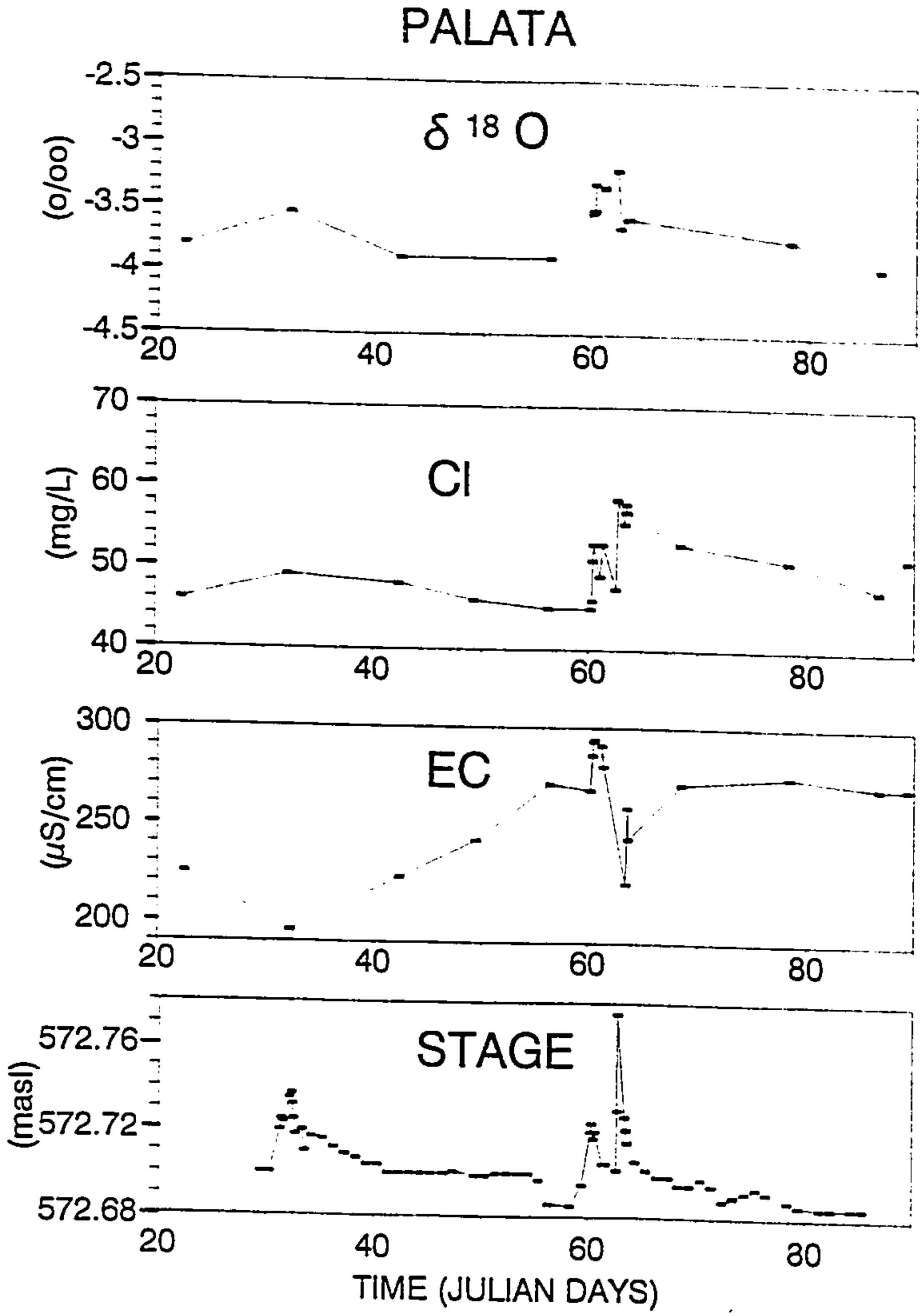

Figure 18. Temporal variations in $\delta^{18}O$, Cl and EC in Palata (Day 1 = January 1, 1992).

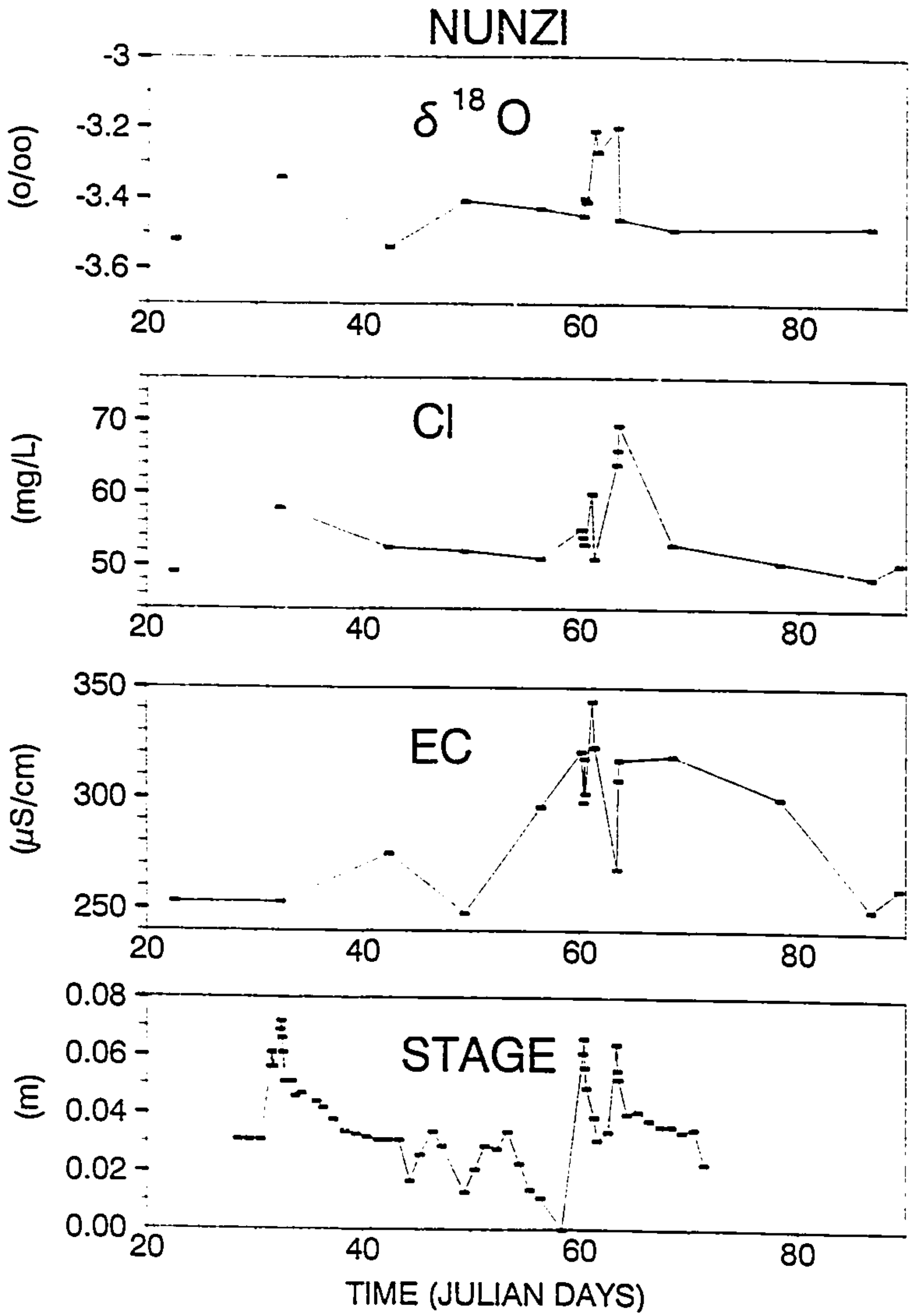

Figure 19. Temporal variations in $\delta^{18}O$, Cl and EC in Nunzi (Day 1 = January 1, 1992).

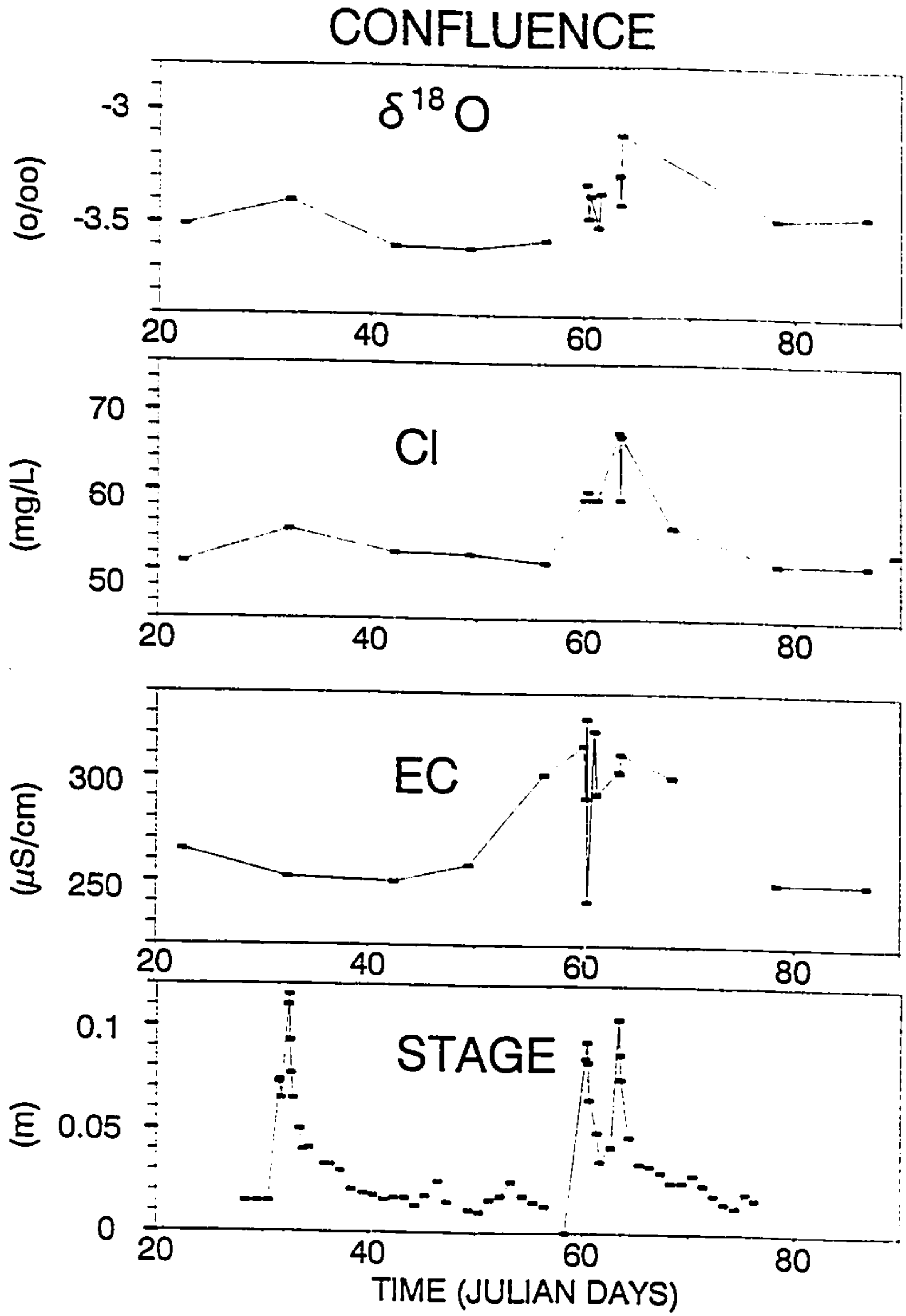

Figure 20. Temporal variations in $\delta^{18}O$, Cl and EC in Confluence (Day 1 = January 1, 1992).

runoff. At the end of storm runoff the isotopic composition of the streamflow returned to baseflow $\delta^{18}O$.

Using mass balance equations and the concentration of ^{18}O in Palata, Nunzi and Confluence, it was found that Palata and Nunzi contributed about 20% and 80%, respectively to the Confluence during low flow. During high flow following Event 1, Palata and Nunzi contributed about 30% and 70%, respectively to the Confluence. During Event 2, both Palata and Nunzi contributed about 50% to the Confluence. The EC values suggest that Palata and Nunzi contributed about 5% and 95%, respectively to the Confluence at low flow.

6.1.6 Chemistry

The various waters in the catchment were analyzed for Cl, EC, NO_3, F, pH and ^{18}O. Chemical data for the water samples from the various sources are given in Appendix C and D.

Low flow EC values and Cl concentration in EB Spring, Palata and Nunzi streams and their confluence are summarized in Table 7. The EC values ranged from 225 to 271 μS/cm, and the Cl concentration varied from 45 to 52 mg/L in the Palata Creek. The average baseflow Cl concentration for Palata Creek was 48.3 mg/L, and the average EC value was 246.2 μS/cm. During stormflow, the Cl concentration in Palata increased by about 5%, and the EC values increased by about

TABLE 7. Baseflow Cl concentration and EC values in the catchment

Stream	Cl (mg/L)			EC (μS/cm)		
	No. of samples	Average value	Standard deviation	No. of samples	Average value	Standard deviation
Palata	8	48.3	2.56	5	246.2	19.4
Nunzi	8	50.9	1.20	5	278.2	23.4
Confluence	8	52.0	0.98	5	277.0	23.2
EB Spring	10	26.6	1.02	6	203.0	14.2

10% (Figure 18). Baseflow EC values for Nunzi Creek ranged from 253 to 319 µS/cm, with an average of 278.2 µS/cm. Baseflow Cl concentration varied from 48.5 to 53.0 mg/L, with an average of 50.9 mg/L. During stormflow the Cl concentration increased by 15% in the stream, and the EC values increased by about 10% (Figure 19).

At the Confluence of Palata and Nunzi streams, the average low flow Cl concentration was 52 mg/L, and EC values ranged from 265 to 311 µS/cm and an average of 277 µS/cm. During stormflow, both the Cl and EC increased by about 10% at the confluence (Figure 20).

The EC is a measure of the total salt concentration in the water. The total dissolved solids (TDS) can be computed by multiplying the recorded EC values by a factor of 0.55 to 0.75 (Hem, 1970). As expected there is some correlation between Cl and EC in the waters of the catchment (Figure 21). As the Cl concentration increases, the EC values increase as well in the waters.

The EC values and Cl concentration in the EB Spring remained constant at about 203 µS/cm and 26.6 mg/L, respectively throughout the study period.

The EC values of the three rainfalls that occurred during the study period varied from 14 to 45 µS/cm. The Cl concentration ranged from 0 to 26 mg/L.

The increase in concentration of Cl and EC values during the hydrograph rise in the streams may be due to

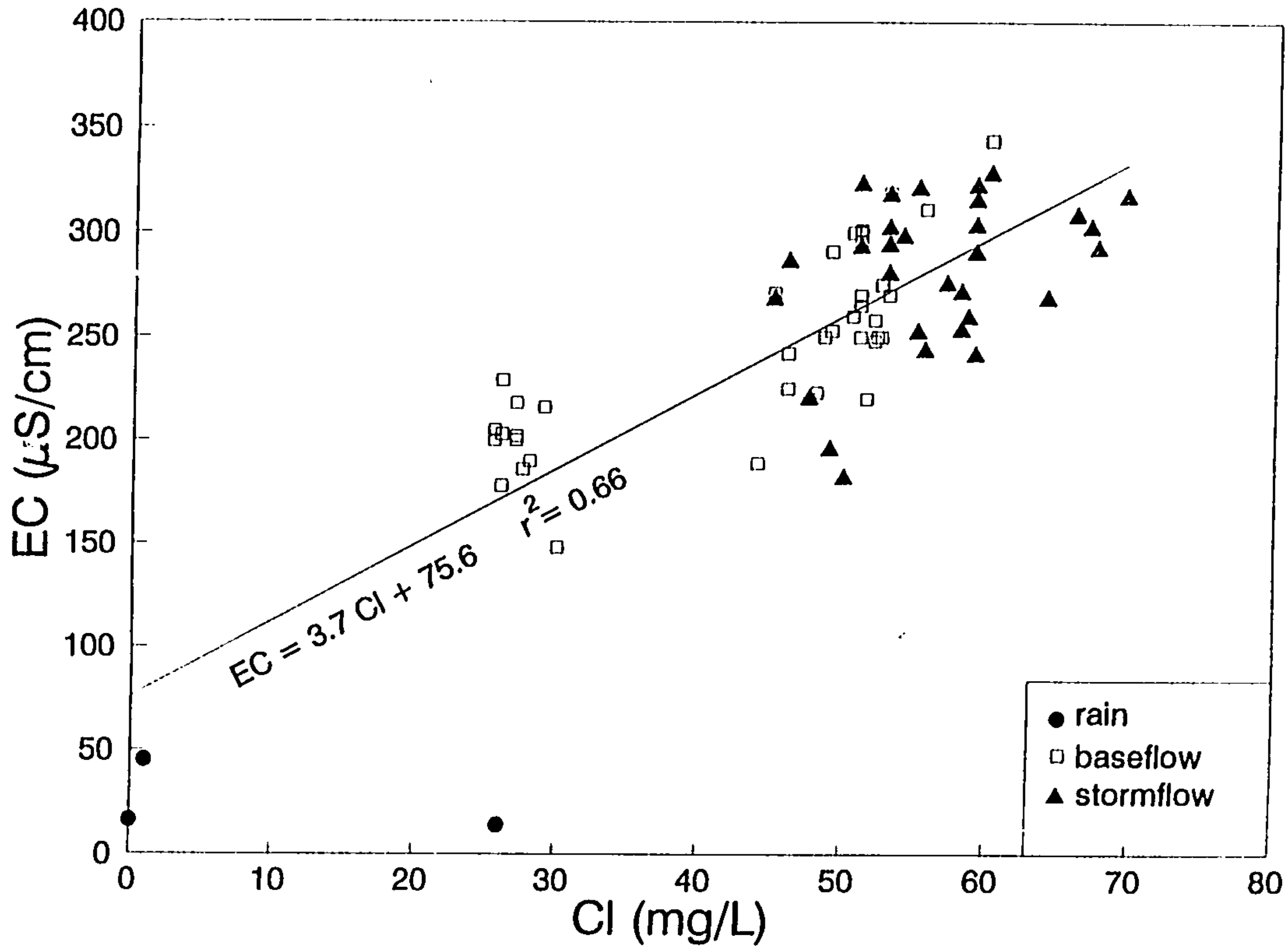

Figure 21. EC versus Cl for the catchment waters.

flushing of dry fallout of solutes from the soil surface by rainfall and groundwater discharging near the streams. Each rainfall event occurred after a prolonged period of drought. The flushing effect makes Cl and EC data unsuitable as natural tracers for hydrogragh separation in the streams. The effect of total solutes flushing occurring during early part of storms following prolonged periods of no storm runoff has been reported by other researchers (Pilgrim et al., 1979; Sklash et al., 1986).

Since the volcanic rocks underlying the area are minor sources of Cl, the possible source of most of the Cl in the groundwater and streams is airborne salts originating from the air-water interface over the Indian Ocean, located about 75 km east of the study area. The Cl is probably deposited in the area by both precipitation and by dry fallout. The average Cl concentration in the groundwater is similar to that of baseflow.

Baseflow nitrate (NO_3) concentration in Palata Creek varied from 5.2 to 10 mg/L, with an average of about 10 mg/L. Nunzi Creek and the confluence had an average baseflow NO_3 concentration of 4.4 mg/L. EB Spring had an average NO_3 concentration of 23.7 mg/L. The average nitrate concentration in the groundwater was about 14 mg/L. During the last stormflow of Day 62 (March 2), the NO_3 concentration increased to 18.9 mg/L in Palata Creek at peak flow.

Unlike most other elements in groundwater, NO_3 is not derived primarily from minerals in the rocks that make up the groundwater reservoir. Therefore, the probable sources of the NO_3 in the groundwater and streams is from manure and fertilizers used by the farmers in the catchment.

The average fluoride concentration in the groundwater was 0.26 mg/L, and in the baseflow varied from 0 to 0.14 mg/L. The average pH in the groundwater and baseflow is close to neutral. These values are similar to those found by Dakin et al. (1992).

6.2 General Hydrology

During the study period, there were only three significant rainfall events in the catchment (Figure 22). Stage data for Palata, Nunzi and Confluence are given in Appendix E. The first and second rainfall events were preceded by long dry periods, and the third rainfall event occurred within 48 hours after the second storm event. Drought of this nature is unusual in the area during this time of the year.

Storm Event 1 occurred on Day 32 (February 1, 1992) producing 20 mm of rain in one hour. Streamflow in the catchment responded to the rainstorm. The stage at Palata Creek rose by 3.7 cm to reach peak flow. Peak stage at Nunzi Creek reached 4.1 cm, and the Confluence stage rose to 10 cm at peak flow. This storm followed 6 mm and 2 mm of

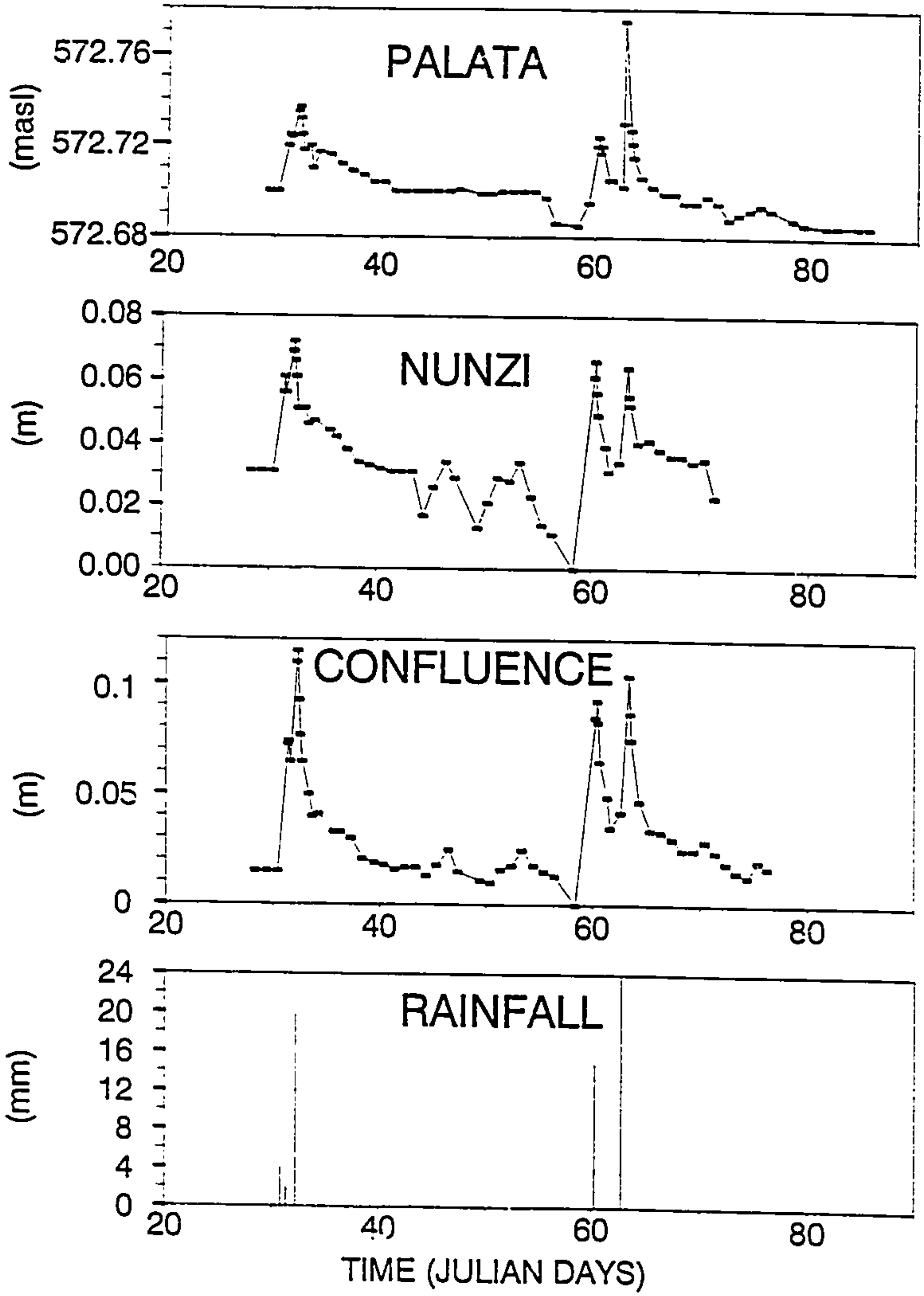

Figure 22. Temporal variation of rainfall and stream stage in Palata, Nunzi and Confluence (Day 1 = January 1, 1992).

rainfall in the previous 24 hours.

Storm Event 2 dropped 15 mm of rain in 45 minutes on Day 60 (February 29). Palata , Nunzi and Confluence stages rose by 3.5 cm, 6.5 cm and 9.8 cm, respectively to peak flow. This storm fell on a dry catchment.

Storm Event 3 produced 24 mm of rain in one hour on Day 62 (March 2). This rainfall occurred within 48 hours after storm Event 2, so the soils were relatively wet. The stage at Palata rose to 7.5 cm at peak flow. Peak flow data for Nunzi and Confluence are not available due to lack of transport during the storm event.

Overland flow during the storm events was observed only along foot paths, animal tracks and roads. The rainfall from the storms did not change the hydraulic heads in the piezometers in wells M1 through M4. However, the groundwater level in piezometers P1 and P2 in driven well D1 at Palata streambed responded very rapidly following onset of the rainstorms (Figure 16). The EB Spring flow was not influenced by the rainstorms, and its flow remained constant at 0.1 L/s throughout the study period. No rainfall water reached any of the throughfall collecting troughs during the storms (Figure 14).

6.3 Hydrograph Separations.

There were three significant rainfall events during the study period. The distribution of these events is shown in

Figure 22. The response of the streamflow isotopic composition to individual rainfall events was used to partition streamflow into groundwater (old water) and rainfall (new water) components. The hydrograph separations were performed by applying the mass balance equation (5). The groundwater stage-groundwater discharge rating curve method was also used to determine groundwater contributions during storm runoff at Palata.

Sklash and Farvolden (1979) have proposed the following conditions for use of environmental isotopes in mass balance hydrogragh separations:

(1) Groundwater and baseflow are characterized by a single isotopic content.

(2) The isotopic content of the event water (rainfall) is significantly different from the groundwater/baseflow.

(3) The rainwater is characterized by a single isotopic content or variations in the isotopic content are documented.

(4) The groundwater/baseflow and vadose water are isotopically equivalent or the vadose water contributions are insignificant.

(5) Surface storage water contributions to the stream are negligible.

Assumption 1 was fulfilled in the catchment since the groundwater from the shallow wells had almost identical isotopic content as the baseflow water. As discussed above, the slight enrichment in the baseflow is probably due to evaporation of surface waters in the streams. The second assumption was fulfilled for storm events 1 and 2 which occurred on Day 32 and Day 60, respectively. The $\delta^{18}O$ value for Event 1 was -2.44 ‰ and the baseflow $\delta^{18}O$ values for Palata, Nunzi and Confluence were -3.82 ‰, -3.48 ‰ and -3.54 ‰, respectively. Storm Event 2 had a $\delta^{18}O$ value of -2.81 ‰ which was again different from the baseflow. Storm Event 3 which occurred on Day 62 violated assumption 2 in that it had $\delta^{18}O$ value of -3.71 ‰ which was almost similar to the baseflow, and consequently had minimal isotopic impact on the streamflow.

Assumption 3 was probably fulfilled since the storms were of short duration and the catchment is small with minimal variation in elevation. The vadose water contributions of assumption 4 were probably insignificant. Partial evidence for this is the fact that no rain water from the storms collected in the throughflow collecting system that was constructed in the catchment, even though this area was near a discharge zone. The catchment has no surface storage, and therefore assumption 5 was fulfilled as well.

6.3.1 Storm Event 1

Storm Event 1 fell on Day 32, dropping 20 mm of rain in one hour. This storm event occurred after a month of no rain, except two small events of 6 and 2 mm which occurred on Day 30 and Day 31, respectively prior to the main event. Peak stream stages at Palata, Nunzi and Confluence were reached in less than two hours after the rain stopped (Figure 22).

The average baseflow (prestorm) $\delta^{18}O$ values for Palata, Nunzi and confluence were -3.82 °/$_{\infty}$, -3.48 °/$_{\infty}$ and -3.54 °/$_{\infty}$, respectively. These values remained almost constant throughout the study period. Therefore, these values were used for C_o in the mass balance equation (5). During peak flow the $\delta^{18}O$ values for Palata, Nunzi and confluence increased to -3.55 °/$_{\infty}$, -3.34 °/$_{\infty}$ and -3.40 °/$_{\infty}$, respectively. These values represent C_s in equation (5). The $\delta^{18}O$ value for the rainfall in storm Event 1 was -2.44 °/$_{\infty}$, and this value was used for C_n in equation (5). Since the stream samples were not taken at a gauging station, the groundwater contribution during storm runoff was estimated by solving for Q_o/Q_s in equation (5), and multiplying by 100 to get percentage groundwater contributions.

Values of the parameters used in equation (5) to solve for the groundwater contributions, Q_o/Q_s during the storm runoff resulting from event 1 are given in Table 8. The calculations for this runoff event show that groundwater contributed 80% in Palata, 86.5% in Nunzi and 87% in the confluence at peak flow. Table 8 also shows that the

TABLE 8. Groundwater component of storm runoff for Event 1 at peak flow

Stream	$\delta^{18}O$ (°/∞)			Q_o/Q_s	Groundwater contribution (%)
	C_o	C_s	C_n		
Palata	-3.82	-3.55	-2.44	0.80	80
Nunzi	-3.48	-3.34	-2.44	0.87	87
Confluence	-3.54	-3.40	-2.44	0.87	87

percentage of groundwater contribution in the storm runoff is greater in Nunzi and Confluence, which were sampled further downstream in the catchment, than Palata. This fact may be attributed in part to the more efficient groundwater drainage in the downstream areas. Partial evidence for this is provided by increase seeps downstream in the catchment.

The chemical tracers EC and Cl could not be used effectively in the hydrograph separation because both EC and Cl increased during the storm runoff in the streams (Figures 18, 19 and 20). The increases in the EC and Cl were probably caused by flushing of salts by the nearstream overland flow and groundwater discharging near the streams. The salts may have accumulated due to extensive evaporation and dry fallout prior to the event.

Another important feature of this storm event was that it caused an instantaneous and rapid response in the near-stream groundwater levels in piezometers P1 and P2 in well D1 at Palata (Figure 16). Data for Palata stage and groundwater stage in well D1 are given in Appendix F. During the storm event, the vertical hydraulic gradient calculated from P1 and P2 increased upward from a prestorm value of 0.025 to about 0.04. The stream remained effluent throughout the event. In well D2, located 34 m away from Palata, the water level reached P1 only after the heads in P1 and P2 in well D1 had reached maximum height. Water levels in wells M1 through M4 located about 500 m away from

Palata were not influenced by the storm event (Figure 2).

Palata streamflow and water-level data from well D1 were used to construct a rating curve of baseflow stage versus groundwater stage (Figure 23). The regression line has a slope of 0.15 and an intercept of 488.9 ($n=25$, $r^2 =0.82$). Palata baseflow stage and groundwater stage data are given in Appendix G. According to the groundwater stage-groundwater discharge rating curve technique, groundwater contributed about 90% during peak flow on Day 32 in Palata. This method could not be applied in Nunzi and Confluence since there were no monitoring wells in their riparian areas.

The baseflow temperature prior to the storm was 25 °C. The temperature of the rain storm was 22 °C. Storm runoff temperature became identical to the rain temperature at Palata, Nunzi and Confluence.

6.3.2 Storm Event 2

Storm Event 2 occurred on Day 60 when 15 mm of rain fell in 45 minutes. Preceding this storm event was an extended dry period of almost a month. Stream stages increased in Palata, Nunzi and Confluence following this storm event (Figure 22).

Again the average baseflow (prestorm) $\delta^{18}O$ values for Palata, Nunzi and Confluence were -3.82 °/oo, -3.48 ‰ and -3.54 ‰, respectively. During peak flow the $\delta^{18}O$ values

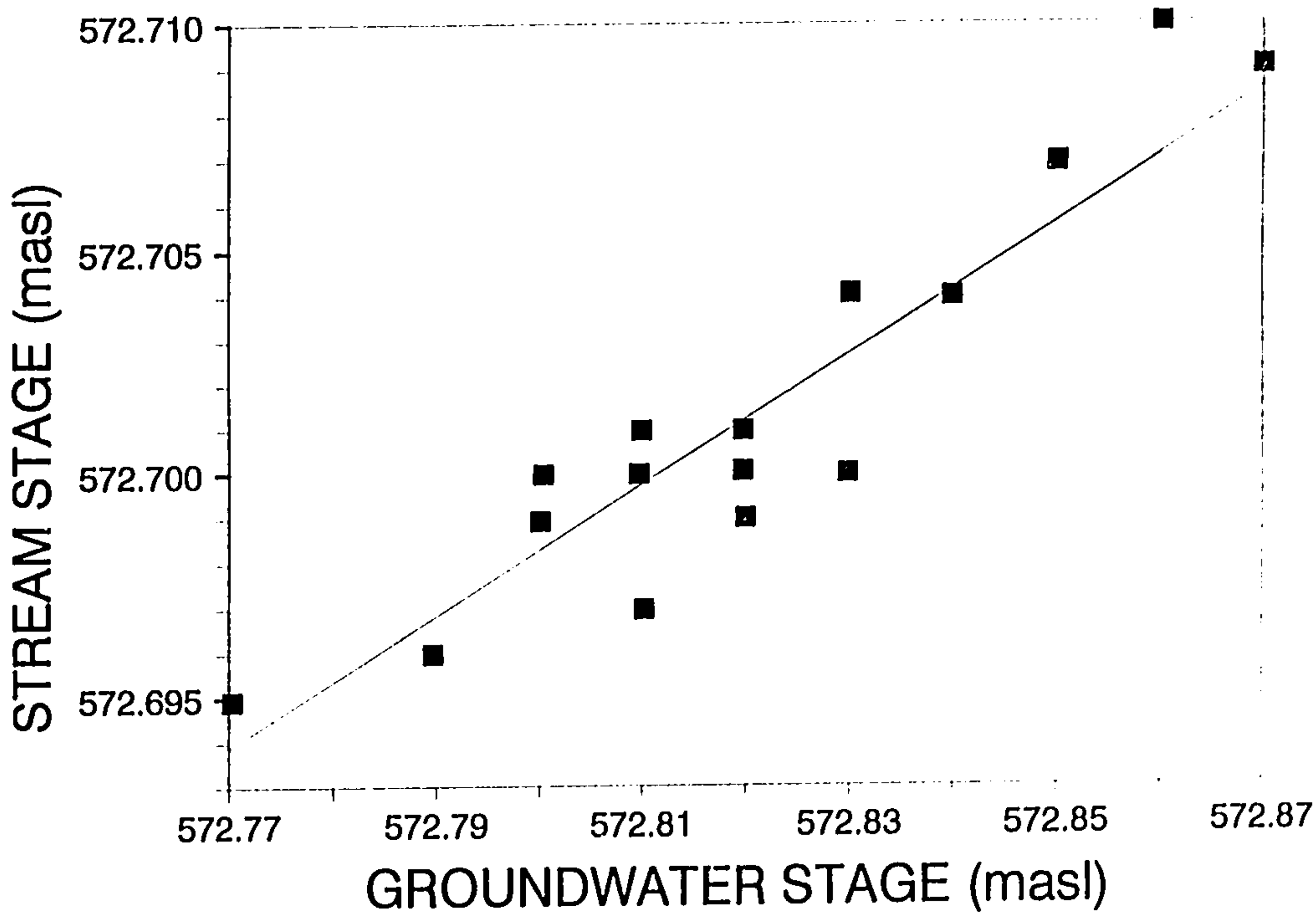

Figure 23. Rating curve of mean groundwater elevation in D1 versus baseflow stage in Palata.

increased to -3.54 $^{o}/_{oo}$, -3.40 $^{o}/_{oo}$ and -3.47 $^{o}/_{oo}$ in Palata, Nunzi and Confluence, respectively. The $\delta^{18}O$ value for storm Event 2 was -2.81 $^{o}/_{oo}$. These values were inserted in equation (5) to solve for the groundwater contribution to the storm runoff event. Table 9 gives the groundwater contributions in Palata, Nunzi and Confluence at peak runoff following storm Event 2. The calculations for this runoff event show that groundwater contributed 72% in Palata, 88% in Nunzi, and 90% in the Confluence. The results in Table 9 also show an increase in the percentage of groundwater contribution downstream. The hydrograph separations for Palata, Nunzi and Confluence for storm Event 2 are shown in Figure 24. The only source of error in the baseflow, stormflow and rain samples is the analytical error for $\delta^{18}O$. The error is the same in all the samples analyzed. Therefore, the estimated uncertainty in the above figures is 5 to 10%.

The groundwater levels in piezometers P1 and P2 in Well D1 again rose very rapidly following storm Event 2 (Figure 16). The Palata stream was effluent throughout the event. The rating curve in Figure 23 was used to estimate groundwater contribution to the storm hydrograph in Palata. According to the groundwater stage-groundwater discharge rating curve technique, groundwater contributed about 90% of the peak flow during storm Event 2.

The temperature of the storm runoff became similar to

TABLE 9. Groundwater component of storm runoff for Event 2 at peak flow

Stream	$\delta^{18}O$ (°/₀₀)			Q_o/Q_t	Groundwater contribution (%)
	C_o	C_t	C_n		
Palata	-3.82	-3.54	-2.81	0.72	72
Nunzi	-3.48	-3.40	-2.81	0.88	88
Confluence	-3.54	-3.47	-2.81	0.90	90

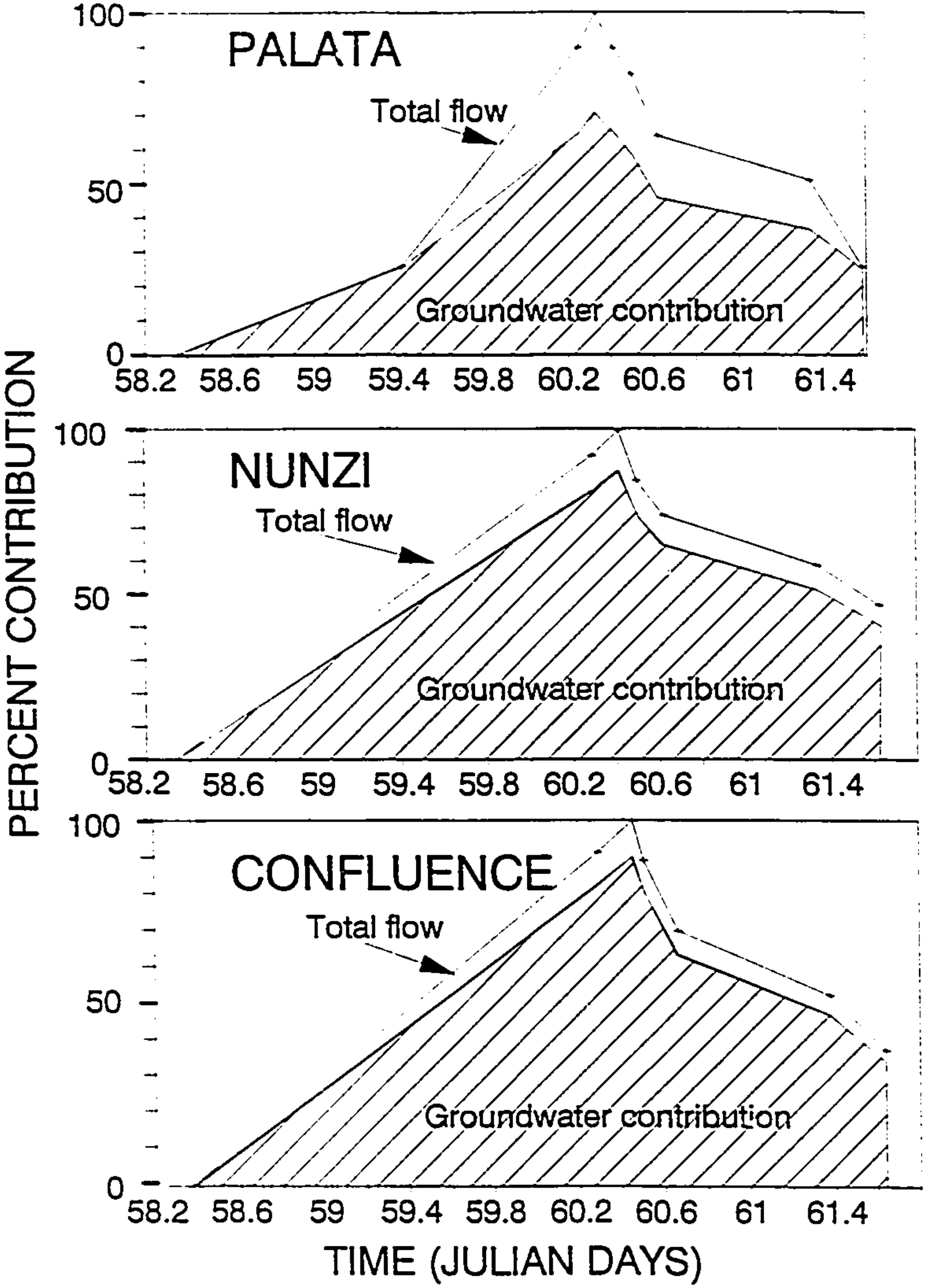

Figure 24. Hydrograph separations for Palata, Nunzi and Confluence during storm Event 2 (Day 1 = January 1, 1992).

the rain temperature. The EC and Cl increased during the storm runoff, and therefore were unsuitable for hydrograph separation.

6.3.3 Storm Event 3

Storm Event 3 occurred on Day 62, producing 24 mm of rain in one hour. This storm fell within 48 hours after Event 2. Therefore, the catchment was relatively wet. The storm caused significant rises in the stream stages (Figure 22). However, since the $\delta^{18}O$ value for the rain storm was -3.71 $^{o}/_{oo}$, hydrograph separation was not possible because this value was almost identical to the baseflow values.

The groundwater levels in piezometers P1 and P2 in well D1 near Palata responded quickly to the rain event (Figure 16). Applying the groundwater stage-groundwater discharge rating curve method, it was found that groundwater contributed over 80% at the peak flow in Palata.

Nitrate increased from a low flow value of 6.6 mg/L to 18.9 mg/L at peak flow in Palata following Event 3 (Figure 25). The nitrate increased was probably due to discharge of nitrate enriched groundwater to the stream. The concentration of nitrate in the groundwater was higher than in the baseflow.

6.3.4 Summary of Storm Runoff Events

The following were observed and deduced as a result of

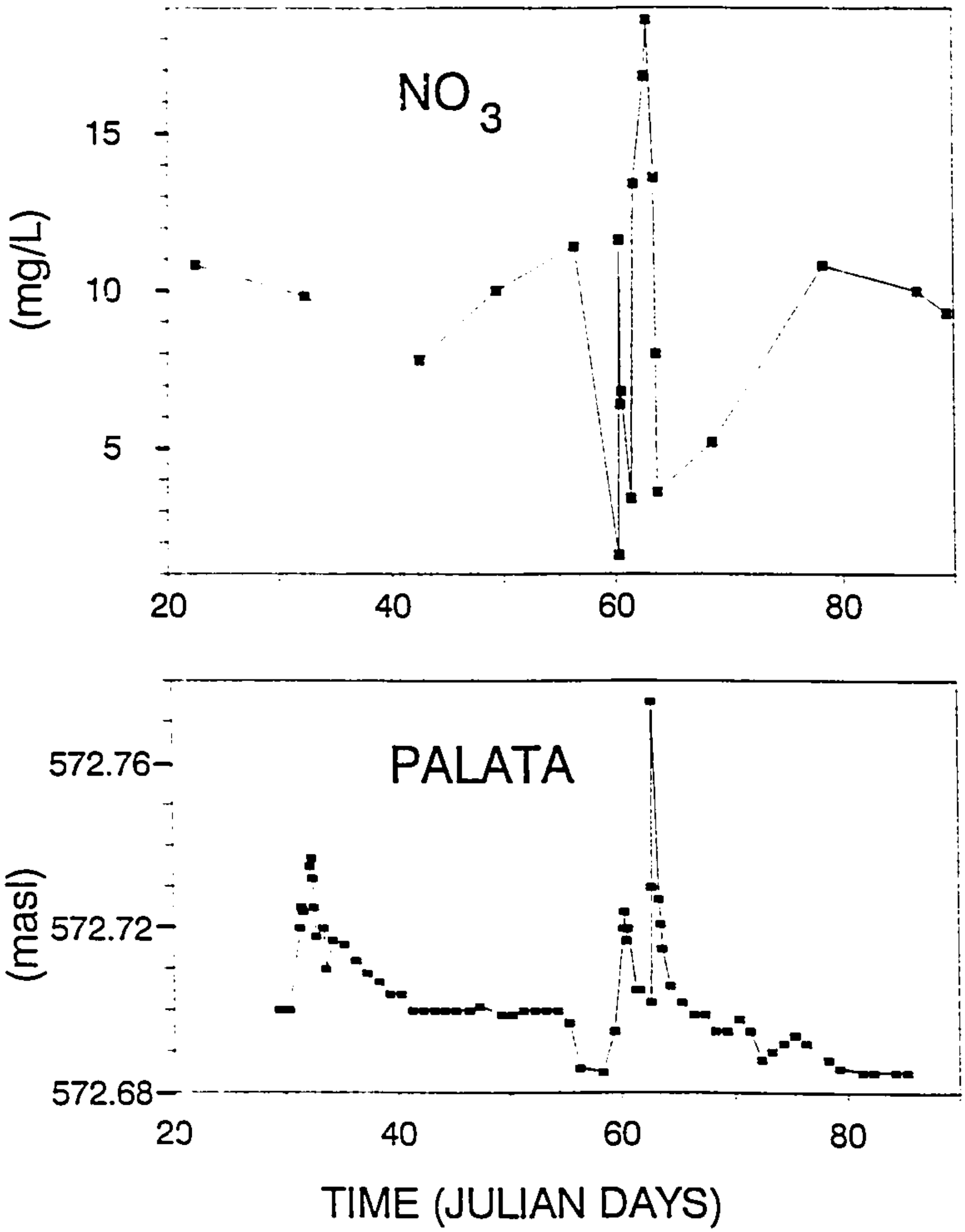

Figure 25. Temporal variations of nitrate in Palata Creek (Day 1 = January 1, 1992).

the three storms that occurred in the catchment:

(1) There was rapid increase in the groundwater levels in the near-stream wells at Palata in response to each rainfall event. The magnitude of the upward vertical hydraulic gradient increased during events.

(2) The rapid increase in the near-stream groundwater levels was followed by the rise in stream water level. However, the timing of the groundwater response and stream water level rise could not be determined precisely since data were recorded manually and regularly.

(3) The groundwater level in well D2 located 34 m away from Palata responded later than in well D1 at the Palata streambed. Water levels in wells M1 through M4 located about 500 m away from Palata did not respond to the rain events.

(4) Baseflow isotopic composition was almost identical to that of shallow groundwater.

(5) There was a slight trend towards enriched $\delta^{18}O$ values in the baseflow downstream due to evaporation.

(6) The variability in the $\delta^{18}O$ between the rainfall events during this study was relatively large and generated smaller but significant fluctuations in the stream isotopic composition.

(7) The rainfall events were detected almost immediately in the streamflow isotopic composition.

(8) A simple mass balance hydrograph separation based on the ^{18}O isotope concentrations for rainfall events 1 and 2 showed that between 70 and 80% of the peak flow hydrograph was due to groundwater contribution in Palata, and between 85 and 90% in Nunzi and confluence.

(9) Storm event 3 had $\delta^{18}O$ value similar to the baseflow stream value and consequently could not be used in the mass balance hydrograph separation.

(10) During storm Event 3, nitrate concentration increased from prestorm value of 6.6 mg/L to 18.9 mg/L in Palata at peak flow.

(11) The temperature of storm runoff changed to the temperature of the rainfall event that initiated it.

(12) Each storm runoff was accompanied by an in increased in EC and Cl. This made both Cl and EC unsuitable for the mass balance hydrograph separation.

(13) According to the groundwater stage-groundwater discharge rating curve method, groundwater contributed about 90% of the peak flow following each rainfall event in Palata.

The groundwater stage-groundwater groundwater discharge rating curve method gave a higher estimate of the groundwater contribution to storm runoff in Palata than the mass balance isotope technique.

Since there is no exact technique available for distinguishing groundwater contribution to storm runoff, one can only examine these techniques by comparison. The isotope data seem to represent the entire catchment, since they represent the mixture of all upstream runoff. Many studies have found that at low temperatures encountered in most catchment studies, the stable isotopes are conservative and are not affected by interaction with rocks or soil (Fritz et al.,1976; Kennedy et al.,1986; and others). Once the rainfall has entered the catchment, the dominant process which affects the abundance of the stable isotopes is physical mixing with waters of different isotopic abundance. On the other hand, the water level data were specific in location and not necessarily representative of the whole catchment. Nevertheless, the important fact here is that both techniques showed significant contribution of groundwater to storm runoff in the catchment. Moreover, the resolution of the apparent discrepancies between the mechanisms of streamflow generation suggested by the hydrochemical and isotopic approaches and those suggested by hydrometric measurements remains a subject of active research.

A possible mechanism to explain the substantial groundwater contribution to streamflow during the storm events in the catchment is groundwater ridging as described by Sklash and Farvolden (1979). The groundwater ridging hypothesis states that where the water table and associated and capillary fringe are near the surface along a stream, rainfall will cause a rapid rise in the water table resulting in increased groundwater flow into the stream. The observed rapid rise in the groundwater levels in the wells close to Palata following onset of rain events, and the increased vertical hydraulic gradients partially prove that groundwater ridging did take place in the catchment. The results of this study are consistent with natural isotopic tracer studies carried out in humid headwater catchments in which groundwater was found to be a significant contributor to storm runoff (Fritz et al.,1976; Sklash et al.,1976, Sklash and Farvolden, 1979; Pearce et al.,1986; Sklash et al.,1986; and others).

The increase of nitrate in Palata Creek following storm Event 3 indicates that groundwater discharge during runoff event is an important factor in runoff quality. It is therefore important to recognize the paths through which agricultural chemicals are being washed to streams for an effective agricultural practice.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The main conclusion from this study is that groundwater dominate storm runoff in the Palata Creek watershed. A simple mass balance hydrograph separation based on the ^{18}O concentrations during the rainfafll events 1 and 2 showed that between 70 and 80% of the peak flow hydrograph was due to groundwater contribution in Palata, and between 85 and 90% in Nunzi and Confluence. The groundwater stage-groundwater discharge rating curve method also showed that groundwater contributed over 80% of the peak flow following each storm runoff in Palata.

The substantial groundwater contribution to streamflow during the storm events is believed to be caused by increased hydraulic gradients near or at the stream channels, which develop quickly after a rainfall event.

Other conclusions from this study are as follows:

(1) The Palata Creek watershed is underlain by a massive rhyolite which is locally weathered. The weathered rhyolite has a hydraulic conductivity of 1.0×10^{-7} m/s.

(2) The soil is generally thin and varies from brown to reddish brown sandy to silty clay. Where the soil is thick, the upper 50 cm contains numerous plant roots with occasional small diameter (less than 1.0 cm) macropores. The soil is acidic with a pH of 5.3.

Organic matter decreases with depth from 2.6% in weight to about 0.3% below 50 cm. The hydraulic conductivity of the soil is of the order of 1.0×10^{-6} m/s.

(3) Areas very close to the stream channels were recharged rapidly by the three storm events. Groundwater in the shallow wells away from the stream channels and the EB Spring were not recharged by the rain storms. It is believed the groundwater and EB Spring are recharged occasionally following very heavy rainfall events.

(4) Baseflow $\delta^{18}O$ composition is almost similar to that of shallow groundwater.

(5) The variability in the $\delta^{18}O$ between the rainfall events during this study was large and it generated smaller but significant fluctuations in the stream isotopic composition. The rainfall was detected almost immediately in the stream isotopic composition.

(6) The groundwater discharge caused nitrate to increased from 6.6 mg/L to 18.9 mg/L in Palata during storm Event 3. This shows that groundwater discharge to streams during storm runoff is an important factor in the runoff quality.

(7) The EC and Cl both increased during storm runoff, and therefore were unsuitable for the mass balance hydrograph separation.

(8) During low flow Palata and Nunzi contributed about 20% and 80%, respectively to the confluence.

7.2 Recommendations

This rainfall-runoff study was affected by the unprecedented drought in the area. However, the following should be considered for future study:

(1) A weir should be constructed very close to the headwaters of Palata, and daily stream discharge monitored. A standard recording rain gauge be installed close to the weir.

(2) A network of small diameter shallow wells equipped with automatic water level recorders and recording tensiometers be installed close to Palata near the weir. The use of continuous water level recorders would give better results than taking readings after a specific time. The tensiometers would determine if the conversion of the capillary fringe into phreatic zone does occur during storm events.

(3) One deep well should be drilled in the catchment to determine if the chemistry and isotopic composition of its water is similar to the shallow groundwater.

(4) Future studies should consider analyzing some water samples for tritium in the wells. This would help in determining the source and when the groundwater was recharged.

(5) More throughflow collectors should be constructed and monitored in different parts in the catchment. Water collected should be analyzed for isotopes and

chemistry.

(6) Since isotope analyses are expensive, future studies should also consider using other tracers that are fairly conservative such as silica.

(7) Soil samples should be taken at strategic areas in the catchment and analyzed for Cl. This will help determine the source of Cl in the groundwater and streams.

(8) More springs and seeps should be sampled and analyzed for isotopes in the area. This may provide some clues as to the recharge mechanism in tne area.

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APPENDIX A

BOREHOLE LOGS

Well	Depth	Geology Description
M1	0-4.0 m	Reddish brown silty clay soil.
	4.0-10.1 m	Brown sandy silty soil with weathered rock fragments.
	10.1-18.3 m	Deeply weathered rhyolite with pink feldspars.
	18.3-20.0 m	Fresh, hard, light grey rhyolite with pink and white feldsars.
M2	0-4.0 m	Dark red, silty clay soil.
	4.0-9.1 m	Beige silty soil with weathered rock fragments.
	9.1-17.5 m	Weathered rhyolite with pink feldspars.
	17.7-18.5 m	Fresh, hard, light grey rhyolite.
M3	0-4.0 m	Maroon to deep red silty clay soil.
	4.0-6.6 m	Deep red, silty clay soil with weathered rock fragments.
	6.6-17.0 m	Weathered rhyolite.
	17.0-20.0 m	Dark grey, hard, fresh rhyolite with white and pink feldspars.
M4	0-5.0 m	Reddish brown silty clay soil.
	5.0-10.1 m	Dark brown, sandy silty clay soil with weathered rock fragments.
	10.1-18.0 m	Weathered reddish brown rhyolite.
	18.0-18.9 m	Fresh, hard, iron stained rhyolite.

APPENDIX B

SINGLE WELL TEST DATA

H=static water level before bailing
Ho=water level soon after bailing
h=depth to water level
H-h=unrecovered head
H-Ho= initial head
K=r**2*ln(L/R)/2LTo

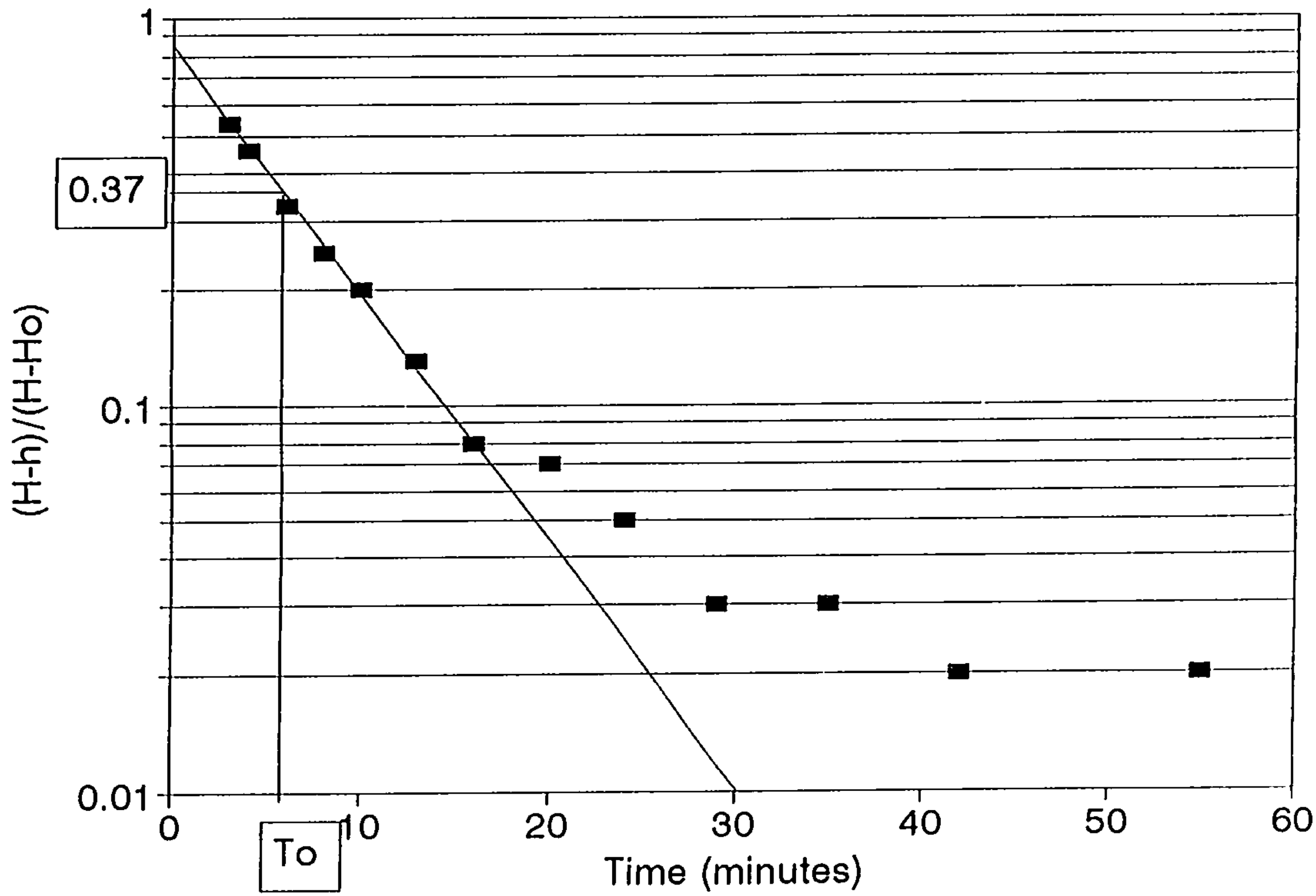
Well= D1, Piezometer P1
Elevation= 573.00 masl
Casing stick up= 1.05 m
H= 572.83 masl Ho= 572.22 masl H-Ho= 0.61 m To=360 s
R=3.25 cm r=0.95 cm L=10 cm

Elevation (masl)	Time (min)	h (masl)	H-h (m)	H-h/H-Ho
573	3	572.5	0.33	0.54
	4	572.55	0.28	0.46
	6	572.63	0.2	0.33
	8	572.68	0.15	0.25
	10	572.71	0.12	0.2
	13	572.75	0.08	0.13
	16	572.78	0.05	0.08
	20	572.79	0.04	0.07
	24	572.8	0.03	0.05
	29	572.81	0.02	0.03
	35	572.81	0.02	0.03
	42	572.82	0.01	0.02
	55	572.82	0.01	0.02

Well= D1, Piezometer P2
H=572.81 masl, Ho=572.53 masl, H-Ho=0.28 m, To=1500 s

Elevation (masl)	Time (min)	h (masl)	H-h (m)	H-h/H-Ho
573				
	3	572.59	0.22	0.81
	4	572.6	0.21	0.77
	6	572.62	0.19	0.71
	8	572.64	0.17	0.65
	10	572.65	0.16	0.61
	13	572.67	0.14	0.55
	16	572.69	0.12	0.48
	20	572.71	0.1	0.42
	24	572.72	0.09	0.39
	29	572.74	0.07	0.32
	35	572.75	0.06	0.29
	42	572.77	0.04	0.23
	55	572.79	0.02	0.16
	70	572.81	0	0.1

Well D1-P1



Well= M1, Piezometer P1
Casing stick up=1.18 m
H=596.24 masl, Ho=594.52 masl, H-Ho=1.72 m, To=600 s
R=7.6 cm r=.95 cm L=100 cm

Elevation (masl)	Time (min)	h (masl)	H-h (m)	H-h/H-Ho
600	1	594.78	1.46	0.85
	2	594.92	1.32	0.77
	3	595.05	1.19	0.69
	4	595.16	1.08	0.63
	6	595.34	0.9	0.52
	8	595.48	0.76	0.44
	10	595.59	0.65	0.38
	13	595.72	0.52	0.3
	16	595.82	0.42	0.24
	20	595.89	0.35	0.2
	24	595.95	0.29	0.17
	29	596.01	0.23	0.13
	35	596.05	0.19	0.11
	42	596.09	0.15	0.09
	55	595.15	0.09	0.05

Well= M1, Piezometer P2
H=596.67 masl, Ho=596.06 masl, H-Ho=0.61 m, To=540 s
R=7.6 cm r=.95 cm L=100 cm

Elevation (masl)	Time (min)	h (masl)	H-h (m)	H-h/H-Ho
600	1	596.15	0.52	0.85
	2	596.2	0.47	0.77
	3	596.25	0.42	0.69
	4	596.29	0.38	0.62
	6	596.36	0.31	0.51
	8	596.42	0.25	0.41
	10	596.46	0.21	0.34
	13	596.52	0.15	0.25
	16	596.56	0.11	0.18
	20	596.6	0.07	0.12
	24	596.62	0.05	0.08
	29	596.64	0.03	0.05
	35	596.65	0.02	0.03
	42	596.66	0.01	0.02
	55	596.67	0	0

Well= M1, Piezometer P3
H=596.67 masl, Ho=596.19 masl, H-Ho=0.48 m, To=72 s
R=7.6 cm r=.95 cm L=100 cm

Elevation (masl)	Time (min)	h (masl)	H-h (m)	H-h/H-Ho
600	1	596.44	0.22	0.47
	2	596.57	0.09	0.19
	3	596.63	0.03	0.06
	4	596.65	0.01	0.02
	6	596.65	0.01	0.02

Well= M2, Piezometer P1
Casing stick up=1.28 m
H=596.86 masl, Ho=595.84 masl, H-Ho=1.02 m, To=1260 s
R=7.6 cm r=.95 cm L=100 cm

Elevation (masl)	Time (min)	h (masl)	H-h (m)	H-h/H-Ho
603.5	1	595.99	0.87	0.85
	2	596.03	0.83	0.81
	3	596.06	0.8	0.78
	4	596.08	0.78	0.76
	6	596.1	0.76	0.75
	8	596.12	0.74	0.73
	10	596.13	0.73	0.72
	13	596.14	0.72	0.71
	16	596.15	0.71	0.7
	20	596.16	0.7	0.69
	24	596.17	0.69	0.68
	29	596.18	0.68	0.67
	35	596.2	0.66	0.65
	42	596.21	0.65	0.64
	55	596.23	0.63	0.62

Well= M2, Piezometer P2
H=596.85 masl, Ho=596.69 masl, H-Ho=0.16 m, To=660 s
R=7.6 cm r=.95 cm L=100 cm

Elevation (masl)	Time (min)	h (masl)	H-h (m)	H-h/H-Ho
603.5	1	596.72	0.13	0.81
	2	596.73	0.12	0.75
	3	596.73	0.12	0.75
	4	596.73	0.12	0.75
	6	596.74	0.12	0.69

Well= M3, Piezometer P1
H=597.75 masl, Ho=596.64 masl, H-Ho=1.11 m, To=1440 s
Casing stick up=1.46 m
R=7.6 cm r=.95 cm L=100 cm

Elevation (masl)	Time (min)	h (masl)	H-h (m)	H-h/H-Ho
608	1	596.75	1	0.9
	2	596.8	0.95	0.86
	3	596.84	0.91	0.82
	4	596.87	0.88	0.79
	6	596.97	0.78	0.7
	8	597	0.75	0.68
	10	597.06	0.69	0.62
	13	597.13	0.62	0.56
	16	597.2	0.55	0.5
	20	597.27	0.48	0.43
	24	597.37	0.41	0.37
	29	597.43	0.32	0.29
	35	597.48	0.27	0.24
	42	597.55	0.2	0.18
	55	597.63	0.12	0.11

Well= M3, Piezometer P2
H=600.08 masl, Ho=599.80 masl, H-Ho=0.28 m, To=1440 s
R=7.6 cm r=.95 cm L=100 cm

Elevation (masl)	Time (min)	h (masl)	H-h (m)	H-h/H-Ho
608	1	599.85	0.23	0.82
	2	599.86	0.22	0.79
	3	599.87	0.21	0.75
	4	599.88	0.2	0.71
	6	599.9	0.18	0.64
	8	599.91	0.17	0.61
	10	599.92	0.16	0.57
	13	599.93	0.15	0.54
	16	599.95	0.13	0.46
	20	599.96	0.12	0.43
	24	599.98	0.1	0.36
	29	599.99	0.09	0.32
	35	600	0.08	0.29
	42	600.01	0.07	0.25
	55	600.02	0.06	0.21

Well= M4, Piezometer P1
Casing stick up= 0.72 m
H=596.42 masl, Ho=596.36 masl, H-Ho=0.06 m, To=102 s
R=7.6 cm r=.95 cm L=100 cm

Elevation (masl)	Time (min)	h (masl)	H-h (m)	H-h/H-Ho
601	1	596.39	0.03	0.5
	2	596.4	0.02	0.33
	3	596.4	0.02	0.33
	4	596.4	0.02	0.33
	6	596.41	0.01	0.17
	8	596.41	0.01	0.17
	10	596.41	0.01	0.17
	13	596.42	0	0

Well= M4, Piezometer P2
H=596.5 masl, Ho=596.20 masl, H-Ho=0.30 m, To=120 s
R=7.6 cm r=.95 cm L=100 cm

Elevation (masl)	Time (min)	h (masl)	H-h (m)	H-h/H-Ho
601	1	596.35	0.17	0.53
	2	596.4	0.12	0.38
	3	596.43	0.09	0.28
	4	596.44	0.08	0.25
	6	596.46	0.06	0.19
	8	596.47	0.05	0.16
	10	596.48	0.04	0.13
	13	596.48	0.04	0.13
	16	596.49	0.03	0.09
	20	596.49	0.03	0.09

Well= M4, Piezometer P3
H=596.50 masl, Ho=596.26 masl, H-Ho=0.24 m, To=210 s
R=7.6 cm r=.95 cm L=100 cm

Elevation (masl)	Time (min)	h (masl)	H-h (m)	H-h/H-Ho
601	1	596.32	0.18	0.75
	2	596.39	0.11	0.46
	3	596.4	0.1	0.42
	4	596.42	0.08	0.33
	6	596.45	0.05	0.21
	8	596.46	0.04	0.17
	10	596.47	0.03	0.13
	13	596.47	0.03	0.13
	16	596.47	0.03	0.13
	20	596.48	0.02	0.08

APPENDIX C

CHEMICAL DATA FOR SURFACE WATERS

CHEMICAL DATA

E=EB SPRING
P=PALATA
N=NUNZI
C=CONFLUENCE
R=RAIN

SITE	MONTH	DAY	HR	MIN	CL (mg/L)	O-18 (o/oo)	NO3 (mg/L)	F (mg/L)	EC LAB	pH LAB	EC FIELD	pH FIELD	TEMP (Deg C)	COMMENTS
R	3	2	18	5	0	-3.71	0	0	30	5.9	16.3	7.14	18.4	RAINWATER
R	2	29	6	0	1	-2.8	0	0	65	6.6	45.4	7.64	22.5	RAINWATER
R	2	1	6	0	26	-2.44	0	0	40	7.4	14	7.05	20.1	RAINWATER
P	2	18	3	10	44	-3.34	14.8	0.2	130	6.9	189	5.7	29.5	BASEFLOW
P	2	18	3	45	30		16.8	0	110	6.4	148	5.2	21	BASEFLOW
E	2	29	9	30	27		13.2	0	160	6.4	202	6.63	22.6	BASEFLOW
E	3	8	11	0	26		22	0	160	7.4	203	8.3	22.5	BASEFLOW
E	1	8	11	0	27		28.4	0	160	6.6	200	5.7	24	BASEFLOW
E	2	18	9	10	26	-4.14	13.2	0	155	6.4	178	7.83	23	BASEFLOW
E	2	1	12	30	50		27	0	145	6.96	181.8	6.88	29.2	STORMFLOW
E	1	21	12	0	27	-4.19	27.2	0	150	6.4	218	6.03	25.5	BASEFLOW
E	3	18	7	23	25.5	-3.99	21.6	0.1	135	6.3	200	6.4	22.6	BASEFLOW
E	3	26	18	9	25.5		23.4	0.12	135	5.95	200	6.3	22.8	BASEFLOW
E	2	11	9	30	27.5	-3.94	19.6	0	155	7.3	186	7.64	23	BASEFLOW
E	1	13	11	15	26		25	0	143	6.3	229	5.69	24.4	BASEFLOW
E	3	3	9	45	28		26.8	0	145	6.4	190	6.69	22.2	BASEFLOW
E	3	29	9	35	25.5	-4.15	24	0.11	125	6	205	6.5	23.5	BASEFLOW
E	3	2	19	30	29		26.2	0	150	6.6	216	7.76	22.6	BASEFLOW
P	1	22	11	0	46	-3.81	10.8	0	185	7.2	225	6.7	25.3	BASEFLOW
P	2	1	6	0	49	-3.55	9.8	0	180	7.4	195.5	7.42	20.2	STORMFLOW
P	2	11	10	0	48	-3.9	7.8	0	180	8	223	7.49	21.4	BASEFLOW
P	2	18	8	45	46		10	0.12	180	7.3	242	7.25	21.9	BASEFLOW
P	2	25	8	4	45	-3.9	11.4	0.15	155	7.2	271	8.13	23.2	BASEFLOW
P	2	29	6	0	45	-3.54	1.6	0.11	160	7.1	268	7.54	22.7	STORMFLOW
P	2	29	8	0	46	-3.52	11.6	0.13	180	6.9	286	7.17	22.6	STORMFLOW
P	2	29	10	0	51		6.4	0.15	190	6.9	293	6.2	22.6	STORMFLOW
P	2	29	12	30	53	-3.31	6.8	0.14	189	6.9	294	7.4	22.5	STORMFLOW
P	3	1	8	15	53	-3.34	3.4	0.14	190	6.9	280	7.65	22.6	STORMFLOW
P	3	1	14	30	49	-3.2	13.4	0.14	175	7	291	7.1	22.6	BASEFLOW
P	3	2	12	45	47.5		16.8	0	160	6.7	220	7.06	21.4	STORMFLOW
P	3	2	18	58	58.5	-3.66	18.6	0	195	6.7	259	7.4	21.9	BASEFLOW
P	3	3	9	15	55.5	-3.59	13.6	0	195	6.6	243	6.48	19.6	BASEFLOW
P	3	3	12	30	58		8	0	185	6.6	271	6.71	20	BASEFLOW
P	3	3	15	4	57	-3.59	3.6	0	180	6.5	275	6.78	20.5	BASEFLOW
P	3	8	11	30	53		5.2	0	185	8	270	8.33	22.5	BASEFLOW
P	3	18	6	55	51	-3.32	10.8	0.13	180	6.8	270	7.78	22.2	BASEFLOW

P	3	26	17	55	47.5	-3.96	10	0.11	165	6.9	220	6.97	21.1	BASEFLOW
P	3	29	9	15	51.5		9.3	0.18	180	6.95	220	7.3	20.1	BASEFLOW
N	1	22	12	0	49	-3.52	8	0	190	7.2	253	7.05	25.3	BASEFLOW
N	2	1	7	0	58	-3.34	0	0	180	7.3	253	7.18	21.3	STORMFLOW
N	2	11	9	0	52.5	-3.54	4	0	450	7.8	275	7.83	22.7	BASEFLOW
N	2	18	10	19	52	-3.41	4.2	0	185	7.1	248	8.22	22.7	BASEFLOW
N	2	25	9	35	51	-3.43	0	0	190	7.2	296	7.24	23.7	BASEFLOW
N	2	29	15	45	55	-3.41	3	0.12	175	7.1	321	6.8	22.5	STORMFLOW
N	2	29	7	30	54	-3.45	3.6	0.15	185	7.3	298	7.57	22.8	STORMFLOW
N	2	29	10	45	53	-3.4	3	0.14	195	7.3	318	6.36	22.5	STORMFLOW
N	2	29	12	20	53	-3.41	9	0.25	250	7.4	302	6.77	22.5	STORMFLOW
N	3	1	15	0	60	-3.27	0.8	0.13	450	7.2	344	6.65	22.5	BASEFLOW
N	3	1	8	45	51	-3.21	0.8	0.12	175	7.2	323	7.74	22.5	STORMFLOW
N	3	3	10	28	64	-3.2	4	0	450	6.5	268	6.5	19.5	STORMFLOW
N	3	3	13	24	66		4	0	450	6.7	308	6.59	20.2	STORMFLOW
N	3	3	15	22	69.5	-3.46	4.2	0	450	6.7	317	6.88	20.9	STORMFLOW
N	3	8	12	0	53	-3.49	22	0	185	7.7	319	7.84	22.5	BASEFLOW
N	3	18	8	6	50.5		4	0.11	175	6.9	300	7.98	22	BASEFLOW
N	3	26	18	32	48.5	-3.48	4	0.1	145	7	250	7.21	20.4	BASEFLOW
N	3	29	10	0	50.5		3.4	0.1	185	6.9	260	7	20.2	BASEFLOW
C	1	22	11	30	51	-3.51	12.2	0	200	7.2	265	7.02	24.4	BASEFLOW
C	2	1	7	0	55	-3.4	23.6	0	195	7.4	252	7.35	21.1	STORMFLOW
C	2	11	8	15	52.2	-3.6	5.5	0	450	7.9	250	8.24	21.5	BASEFLOW
C	2	18	10	48	52	-3.61	3	0	200	7.9	258	8.56	22.5	BASEFLOW
C	2	25	10	12	51	-3.57	4	0	195	7.5	301	7.9	23.4	BASEFLOW
C	2	29	16	0	59	-3.37	5.8	0	185	7.7	315	7.45	22.5	STORMFLOW
C	2	29	7	0	59	-3.32	6.8	0	190	7.8	290	7.8	22.8	STORMFLOW
C	2	29	11	0	60	-3.47	5.8	0	185	7.6	328	6.65	22.5	STORMFLOW
C	3	1	15	20	59	-3.36	13.8	0	195	7.6	241	7.4	22.5	STORMFLOW
C	3	1	9	0	59	-3.51	6	0	450	7.6	322	7.28	22.6	STORMFLOW
C	3	3	10	53	67.5	-3.28	8	0	450	6.7	292	7.36	18.4	STORMFLOW
C	3	3	13	46	59	-3.41	4.2	0	195	6.5	303	7.56	20.2	STORMFLOW
C	3	3	15	40	67	-3.1	5	0	450	6.6	302	6.91	19.9	STORMFLOW
C	3	8	12	15	55.5		5.2	0	200	7.9	311	8.9	22.5	BASEFLOW
C	3	18	8	27	51	-3.47	4	0.15	150	7.2	300	8.29	21.4	BASEFLOW
C	3	26	18	53	51	-3.45	5.4	0.13	170	7.3	250	8.11	21	BASEFLOW
C	3	29	10	15	52.5		7.6	0.12	150	7.4	250	7.15	20.8	BASEFLOW

APPENDIX D

CHEMICAL DATA FOR GROUNDWATER

BOREHOLE CHEMISTRY

WELL	MO	DAY	HR	MIN	CL (mg/L)	NO3 (mg/L)	F (mg/L)	EC LAB	pH LAB	EC FIELD	pH FIELD	TEM (Deg C)
M1-P1	2	20	13	59	28	0	0.14	500	7.9	381	8.54	30.1
M1-P2	2	20	13	30	38	4.6	0.32	475	7.92	665	8.08	30.5
M2-P1	2	20	14	15	41	7	0.3	700	7.8	709	7.86	32.5
M2-P2	2	20	14	35	31	17	0.19	1050	7.8	1368	7.73	35
M3-P1	2	20	15	20	38	35.2	0.18	475	7.8	452	8.34	35.1
M3-P2	2	20	16	0	38	5.8	0.17	700	8.1	752	8.72	32
M4-P1	2	20	11	0	63	20.8	0.28	700	8	864	8.31	30.8
M4-P2	2	20	11	50	57	14	0.58	900	8.4	1105	8.23	32.5
M4-P4	2	20	12	55	57	8	0.41	850	8.1	1046	7.56	31
D1-P1	1	22	10	30	49	15.2	0.1	230	7.8	300	7.9	25.3
D1-P1	2	11	10	15	50	10	0	218	8.1	250	7.8	21.4
D1-P1	2	25	8	25	51	16	0	210	7.9	270	8.1	23.2
D1-P1	3	18	7	50	50	14.5	0	200	7.8	275	8	22.2
D1-P1	3	29	9	20	49	15	0.1	210	6.9	250	7.2	20.1

APPENDIX E

STAGE DATA FOR PALATA, NUNZI AND CONFLUENCE

PALATA: STAGE vs TIME

MONTH	DATE	HOUR	MINUTE	STAGE (m)	COMMENTS
1	28	8	0	0.015	BASEFLOW
1	29	10	30	0.015	BASEFLOW
1	30	9	15	0.015	BASEFLOW
1	31	8	0	0.035	STORMFLOW
1	31	12	0	0.04	STORMFLOW
1	31	15	0	0.039	STORMFLOW
2	1	6	0	0.05	STORMFLOW
2	1	9	0	0.052	STORMFLOW
2	1	11	0	0.047	STORMFLOW
2	1	14	0	0.04	STORMFLOW
2	1	18	0	0.033	STORMFLOW
2	2	9	0	0.035	STORMFLOW
2	2	14	0	0.025	STORMFLOW
2	3	6	0	0.032	STORMFLOW
2	4	6	0	0.031	STORMFLOW
2	5	7	0	0.027	STORMFLOW
2	6	7	19	0.024	BASEFLOW
2	7	8	28	0.022	BASEFLOW
2	8	7	56	0.019	BASEFLOW
2	9	8	20	0.019	BASEFLOW
2	10	8	52	0.015	BASEFLOW
2	11	7	13	0.015	BASEFLOW
2	12	8	24	0.015	BASEFLOW
2	13	7	42	0.015	BASEFLOW
2	14	6	48	0.015	BASEFLOW
2	15	11	50	0.015	BASEFLOW
2	16	8	0	0.015	BASEFLOW
2	18	8	40	0.014	BASEFLOW
2	19	7	45	0.014	BASEFLOW
2	20	7	35	0.015	BASEFLOW
2	21	8	8	0.015	BASEFLOW
2	22	8	17	0.015	BASEFLOW
2	23	9	44	0.015	BASEFLOW
2	24	9	27	0.012	BASEFLOW
2	25	7	44	0.011	BASEFLOW
2	27	8	6	0	BASEFLOW
2	28	10	0	0.01	BASEFLOW
2	29	6	0	0.035	STORMFLOW
2	29	8	0	0.039	STORMFLOW
2	29	10	0	0.035	STORMFLOW
2	29	12	30	0.032	STORMFLOW
2	29	15	0	0.025	STORMFLOW
3	1	8	15	0.02	BASEFLOW
3	1	14	30	0.01	BASEFLOW
3	2	15	9	0.017	BASEFLOW
3	2	17	45	0.045	STORMFLOW
3	2	18	58	0.09	STORMFLOW
3	3	9	15	0.042	STORMFLOW
3	3	12	23	0.036	STORMFLOW
3	3	15	3	0.03	STORMFLOW
3	4	8	37	0.021	STORMFLOW
3	5	8	59	0.017	BASEFLOW
3	6	10	22	0.014	BASEFLOW
3	7	9	15	0.014	BASEFLOW
3	8	7	48	0.01	BASEFLOW
3	9	8	40	0.01	BASEFLOW
3	10	9	7	0.013	BASEFLOW

NUNZI: STAGE vs TIME

MONTH	DAY	HOUR	MINUTE	STAGE (m)	COMMENTS
1	28	8	18	0.031	BASEFLOW
1	29	9	0	0.031	BASEFLOW
1	30	10	15	0.031	BASEFLOW
1	31	10	50	0.056	STORMFLOW
1	31	12	0	0.061	STORMFLOW
1	31	15	0	0.056	STORMFLOW
2	1	7	0	0.069	STORMFLOW
2	1	9	0	0.072	STORMFLOW
2	1	11	0	0.066	STORMFLOW
2	1	14	0	0.061	STORMFLOW
2	1	18	0	0.051	STORMFLOW
2	2	9	0	0.051	STORMFLOW
2	2	17	0	0.046	STORMFLOW
2	3	6	0	0.047	STORMFLOW
2	4	17	0	0.044	STORMFLOW
2	5	7	0	0.042	STORMFLOW
2	6	6	45	0.038	STORMFLOW
2	7	8	6	0.034	STORMFLOW
2	8	8	18	0.033	STORMFLOW
2	9	8	45	0.032	BASEFLOW
2	10	9	16	0.031	BASEFLOW
2	11	8	49	0.031	BASEFLOW
2	12	8	44	0.031	BASEFLOW
2	13	8	4	0.017	BASEFLOW
2	14	7	33	0.026	BASEFLOW
2	15	11	35	0.034	BASEFLOW
2	16	8	30	0.029	BASEFLOW
2	18	10	30	0.013	BASEFLOW
2	19	8	30	0.021	BASEFLOW
2	20	7	50	0.029	BASEFLOW
2	21	9	15	0.028	BASEFLOW
2	22	8	32	0.034	BASEFLOW
2	23	10	21	0.023	BASEFLOW
2	24	10	3	0.014	BASEFLOW
2	25	9	34	0.011	BASEFLOW
2	27	8	48	0	BASEFLOW
2	29	7	30	0.061	STORMFLOW
2	29	10	45	0.066	STORMFLOW
2	29	12	20	0.056	STORMFLOW
2	29	15	45	0.049	STORMFLOW
3	1	8	45	0.039	STORMFLOW
3	1	15	0	0.031	BASEFLOW
3	2	15	48	0.034	BASEFLOW
3	3	10	28	0.064	STORMFLOW
3	3	13	29	0.055	STORMFLOW
3	3	15	22	0.052	STORMFLOW
3	4	9	21	0.04	STORMFLOW
3	5	9	36	0.041	STORMFLOW
3	6	8	56	0.038	STORMFLOW
3	7	10	8	0.036	BASEFLOW
3	8	9	0	0.036	BASEFLOW
3	9	9	30	0.034	BASEFLOW
3	10	10	30	0.035	BASEFLOW
3	11	9	28	0.023	BASEFLOW

CONFLUENCE: STAGE vs TIME

MONTH	DAY	HOUR	MINUTE	STAGE (m)	COMMENTS
1	28	8	15	0.015	BASEFLOW
1	29	10	30	0.015	BASEFLOW
1	30	11	0	0.015	BASEFLOW
1	31	10	45	0.073	STORMFLOW
1	31	12	0	0.074	STORMFLOW
1	31	15	0	0.065	STORMFLOW
2	1	7	0	0.11	STORMFLOW
2	1	9	0	0.115	STORMFLOW
2	1	11	0	0.093	STORMFLOW
2	1	14	0	0.077	STORMFLOW
2	1	18	0	0.065	STORMFLOW
2	2	9	0	0.05	STORMFLOW
2	2	17	0	0.04	STORMFLOW
2	3	6	0	0.041	STORMFLOW
2	4	17	0	0.033	STORMFLOW
2	5	7	0	0.033	STORMFLOW
2	6	6	50	0.03	STORMFLOW
2	7	8	15	0.021	STORMFLOW
2	8	11	43	0.019	STORMFLOW
2	9	8	57	0.018	STORMFLOW
2	10	9	24	0.016	STORMFLOW
2	11	8	28	0.017	STORMFLOW
2	12	8	57	0.017	STORMFLOW
2	13	8	14	0.013	BASEFLOW
2	14	7	40	0.018	BASEFLOW
2	15	11	30	0.025	BASEFLOW
2	16	8	45	0.015	BASEFLOW
2	18	10	59	0.011	BASEFLOW
2	19	9	0	0.01	BASEFLOW
2	20	7	59	0.016	BASEFLOW
2	21	9	22	0.018	BASEFLOW
2	22	8	39	0.025	BASEFLOW
2	23	10	30	0.018	BASEFLOW
2	24	10	14	0.015	BASEFLOW
2	25	10	8	0.013	BASEFLOW
2	27	8	56	0	BASEFLOW
2	29	7	0	0.085	STORMFLOW
2	29	11	0	0.093	STORMFLOW
2	29	12	10	0.083	STORMFLOW
2	29	16	0	0.065	STORMFLOW
3	1	9	0	0.049	STORMFLOW
3	1	15	20	0.035	STORMFLOW
3	2	15	56	0.042	STORMFLOW
3	3	10	48	0.104	STORMFLOW
3	3	13	46	0.087	STORMFLOW
3	3	15	40	0.075	STORMFLOW
3	4	9	34	0.047	STORMFLOW
3	5	9	46	0.034	STORMFLKOW
3	6	9	23	0.033	STORMFLOW
3	7	10	30	0.03	STORMFLOW
3	8	9	20	0.025	STORMFLOW
3	9	10	10	0.025	STORM
3	10	10	38	0.029	STORMFLOW
3	11	9	41	0.024	STORMFLOW
3	12	9	16	0.019	STORMFLOW
3	13	8	46	0.015	BASEFLOW
3	14	9	40	0.013	BASEFLOW
3	15	10	0	0.02	BASEFLOW
3	16	6	45	0.017	BASEFLOW

APPENDIX F

PALATA AND WELL D1 STAGE DATA

PALATA STAGE vs GROUNDWATER STAGE (D1)

MONT	DAY	HOUR	MINUTE	STREAM STAGE (masl)	GROUNDWATER STAGE P1 (masl)	P2 (masl)
1	28	10	15	572.7	572.8	572.78
1	29	12	30	572.7	572.8	572.78
1	30	8	20	572.7	572.8	572.78
1	31	8	0	572.72	572.89	572.88
1	31	12	0	572.725	572.95	572.9
1	31	15	0	572.724	572.94	572.93
2	1	6	0	572.735	572.97	572.96
2	1	9	0	572.737	572.98	572.95
2	1	11	0	572.732	572.96	572.95
2	1	14	0	572.725	572.95	572.93
2	1	18	0	572.718	572.95	572.93
2	2	9	0	572.72	572.94	572.93
2	2	14	0	572.71	572.91	572.9
2	3	6	0	572.717	572.92	572.91
2	4	6	0	572.716	572.91	572.9
2	5	7	0	572.712	572.9	572.89
2	6	7	19	572.709	572.87	572.86
2	7	8	28	572.707	572.85	572.83
2	8	7	56	572.704	572.84	572.83
2	9	8	20	572.704	572.83	572.81
2	10	8	52	572.7	572.81	572.79
2	11	7	13	572.7	572.8	572.79
2	12	8	24	572.7	572.82	572.8
2	13	7	42	572.7	572.82	572.79
2	14	6	48	572.7	572.81	572.78
2	15	11	50	572.7	572.82	572.79
2	16	8	0	572.701	572.82	572.78
2	18	8	40	572.699	572.82	572.78
2	19	7	45	572.699	572.8	572.78
2	20	7	35	572.7	572.81	572.78
2	21	8	8	572.7	572.83	572.8
2	22	8	17	572.7	572.81	572.8
2	23	9	44	572.7	572.82	572.8
2	24	9	27	572.697	572.81	572.77
2	25	7	44	572.686	572.79	572.77
2	27	8	6	572.685	572.77	572.75
2	28	10	0	572.595	572.83	572.8
2	29	6	0	572.72	572.88	572.86
2	29	8	0	572.724	572.89	572.87
2	29	10	0	572.72	572.88	572.86
2	29	12	30	572.717	572.87	572.85
2	29	15	0	572.72	572.86	572.85
3	1	8	15	572.705	572.88	572.86
3	1	14	30	572.705	572.88	572.86
3	2	15	9	572.702	572.87	572.85
3	2	17	45	572.73	572.94	572.92
3	2	18	58	572.775	572.96	572.93
3	3	9	15	572.727	572.95	572.93
3	3	12	23	572.721	572.95	572.93
3	3	15	3	572.715	572.94	572.92
3	4	8	37	572.706	572.91	572.89
3	5	8	59	572.702	572.89	572.87
3	6	10	22	572.699	572.87	572.85
3	7	9	15	572.699	572.87	572.85
3	8	7	48	572.695	572.85	572.83
3	9	8	40	572.695	572.85	572.83
3	10	9	9	572.698	572.85	572.83
3	11	8	32	572.695	572.85	572.84
3	12	8	15	572.688	572.84	572.83
3	13	7	44	572.69	572.85	572.83
3	14	8	35	572.692	572.85	572.83
3	15	8	5	572.694	572.85	572.83
3	16	7	0	572.692	572.83	572.81
3	18	7	5	572.688	572.81	572.8
3	19	7	57	572.686	572.8	572.79
3	21	8	59	572.685	572.79	572.78
3	22	8	52	572.685	572.78	572.77
3	24	7	40	572.685	572.78	572.77
3	25	8	35	572.685	572.8	572.79

APPENDIX G

PALATA BASEFLOW AND WELL D1 STAGE DATA

PALATA: BASEFLOW STAGE vs GROUNDWATER STAGE

MONTH	DAY	BASEFLOW STAGE (masl)	GROUNDWATER STAGE (masl)
1	28	572.7	572.8
1	29	572.7	572.8
1	30	572.7	572.8
2	6	572.709	572.87
2	7	572.707	572.85
2	8	572.704	572.84
2	9	572.704	572.83
2	10	572.7	572.81
2	11	572.7	572.8
2	12	572.7	572.82
2	13	572.7	572.82
2	14	572.7	572.81
2	15	572.7	572.82
2	16	572.701	572.82
2	18	572.699	572.82
2	19	572.699	572.8
2	20	572.7	572.81
2	21	572.7	572.83
2	22	572.7	572.81
2	23	572.7	572.82
2	24	572.697	572.81
2	25	572.696	572.79
2	27	572.695	572.77
2	28	572.701	572.81
2	29	572.71	572.86

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