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Agroecology hydrology and conservation of ephemeral streams and alluvial fans Zuni Pueblo New Mexico

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AGROECOLOGY, HYDROLOGY, AND CONSERVATION OF EPHEMERAL STREAMS AND ALLUVIAL FANS, ZUNI PUEBLO, NEW MEXICO

by

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Abstract

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Agroecology, hydrology, and conservation of ephemeral streams and alluvial fans, Zuni Pueblo, New Mexico.

Director: Stephen F. Siebert SFS

Zuni farmers grow corn (*Zea mays*) on alluvial soils farmed for as long as 2000 years. These studies focus on traditional knowledge and agroecology of alluvial soils that have key cultural, ecological, and hydrological functions but are vulnerable to erosion in the dynamic semiarid environment. Collaboration with local Zunis during this research changed fundamental scientific assumptions about alluvial fan agroecology in unanticipated ways that contribute to the relevancy of this work. Zuni rain fed farming has been portrayed as irrigation where ephemeral storm flows must supplement rainfall. Collaborative fieldwork and non-structured interviews show that Zuni farmers prioritize flood deposits and conserving depositional regimes more than diverting runoff, and that crops can be grown with rainfall alone. Hydrological data suggests that stormwater irrigation is infeasible; ephemeral streams flow an average of once in 1.5 to two years. Historical evidence shows decline in rain fed farming coincides with accelerated arroyo cutting and suggests that Zuni farming is effective conservation. Analyses of watershed plant-soil-landform interactions show that upland slopes provide runoff, sediment, and organic debris responsible for alluvial soil productivity. Forest litter from woodlands decomposes as it moves downslope. SOM peaks on steep slopes under pinyon-juniper (*Pinus edulis-Juniperus* spp.) cover, but plant-available N and P from decomposing OM increase down hillslopes and ephemeral streams, peaking in alluvial fan soils. Rainfall intensity and runoff-erosion data suggest that frequent minor showers drive decomposition and selectively transport decomposed OM. Less frequent floods flush slopes and channels, depositing mixed sediment and OM on alluvial fans. An in-situ decomposition study in fresh flood-deposited soils and adjacent incised terraces suggests that frequent freeze-thaw and drying-rewetting cycles cause rapid decomposition that may deplete soil fertility without fresh OM from floods. Soil texture analysis suggests that exclusion of flushing flows also deteriorates soil hydrological properties. Traditional conservation methods, evaluated with pre- and post-treatment surveys, proved to be rapid, low-cost, and effective for preventing down cutting and restoring depositional regimes. Brush dams act as permeable energy dissipaters during moderate flows and contribute to channel-modifying debris jams during floods. This research supports alternative perspectives and approaches to conservation, restoration and management in dynamic semiarid environments where many conventional approaches have failed.

Dedication

*To the memory of Martin Holm, Blue Tanttari, and Andrew Laahty,
who each had their own unique and fierce commitment to
people, agriculture, and environment.*

*And to all my friends in the Zuni Sustainable Agriculture Project,
1995 to 1998*

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Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation, the project director, or the co-principle investigators of the larger research project.

Table of Contents

List of Tables

List of Figures

Introduction

Declining health and cultural loss among indigenous people is often a function of socio-economic movement away from the land, and away from their own knowledge and wisdom, as their means of subsistence (Campbell, 1989; Shapiro, 1997). Nowhere is this relationship more clear than on the Zuni Indian Reservation where lifestyle-related illnesses like diabetes, and depression manifested as alcoholism and suicide, take a huge toll (Narayan, 1997; Westlake and May, 1986). This same relationship also pertains to the land itself: natural resources that sustained millennia of cultural development deteriorate as social and economic changes remove native people from their lands (Durning, 1992). If a cause-and-effect relationship exists between the health of the people and the health of the land, government-imposed management systems that are culturally and environmentally inappropriate are partially responsible (Cleveland et al., 1995; Hurt, 1987; White, 1983). Environmental degradation often occurs when local people are denied the right to care for their land as they have for generations. Scientists are beginning to recognize that human activities can moderate effects of environmental change and that cessation of specific long-term human interactions with soils, plants, and animals can degrade environmental quality (Arno et al., 1995; Ellis and Swift, 1988; Nugent, 1991).

Scientists' long-running neglect of a human role in environmental change is strikingly clear in the southwestern U.S. where decades of contentious scientific debate over the causes of accelerated erosion ignore what many Native Americans take for granted: that Native Americans were caretakers of the Earth and degradation results when the U.S. government denied them that right. Such disrespect for local knowledge and

wisdom underlies the almost complete distrust of science that is characteristic of many local people (Deloria, 1997).

The two-way disrespect between scientists and local people is not limited to indigenous peoples; I witnessed the same type of disregard growing up on a farm in Iowa. Believing themselves to be conscientious and progressive, farmers follow the advice of extension agents and university experts who urge them to forsake local environmental knowledge often without any understanding of what this pertains. Farmers often discover a few years later that the winds of scientific fashion have changed: that they should never have applied so much fertilizer, or innovative pesticides touted by government-supported researchers ended up contaminating their groundwater.

A history of this type of interaction leads to extreme skepticism on the part of farmers. Research institutions respond with sophisticated programs dedicated to the psychology and sociology of "technology transfer," to overcome farmer skepticism blamed on backwardness and lack of education but largely created by the fleeting nature of scientific "fact" (Kuhn, 1970). Rarely, it seems, do researchers take time to listen to local people talk about natural resources, to learn what they know, or to understand their more holistic perceptions of agriculture, society, and environment (Kloppenburg, 1991).

I do not mean to imply that all local people possess superior understanding of their ecology and agriculture, or that all their actions are compatible with long-term sustainability. In fact, loss of genuine local knowledge and wisdom contributes to environmental degradation; many local people do not possess appropriate local knowledge and are not able to manage natural resources sustainably. However, subsistence agriculture and hunting-gathering for time periods spanning many

generations inevitably creates genuine knowledge of environmental limits, responses, and ranges of possibility. The late Andrew Laahty, former leader of the Zuni Sustainable Agriculture Project (ZSAP) with which I worked closely during my dissertation research, captured this concept concisely: "To old people, sustainability is survival." This proclamation – sustainability is survival – became a sort of working motto for ZSAP because it explains the fragile relationship between human subsistence and the complex semiarid environment.

Ecologists and other scientists are slowly recognizing the legitimacy of local knowledge (Berkes et al., 2000; Ford and Martinez, 2000). But this long-overdue credibility still seems far from real, broad-scale implementation. Actual incorporation of local knowledge may come only on a case-by-case basis as ecological disaster encourages local organizations to wrench control from exogenous agencies.

This research focuses on traditional Zuni knowledge and agroecological functioning of alluvial zones in ephemeral streams on the Zuni Indian Reservation. These key landforms lie below the mouths tributary ephemeral streams that drain upland mesas; where runoff flows spread and deposit sediments before becoming constricted once again as they merge with higher order stream courses. Though a relatively minor part of the total landscape, these small alluvial fans and flood zones have important cultural, hydrological, and ecological functions (Bull, 1997). Two interrelated characteristics may underlie this importance, which is reflected in Zuni soil terms and agricultural knowledge documented by Pawluk (1995) and Ford (1985). First, the mixed sandy sediments and organic debris deposited by floods have excellent water-absorbing and nutrient-cycling characteristics that enable Zuni farmers to produce highly

consumptive crops like corn (*Zea mays*). Second, these landforms are often near geomorphic threshold conditions, meaning that relatively minor stimuli, such as intense rainfall events or human activities, can cause major changes through either incision or deposition (Goudie, 1994). This makes alluvial zones amenable to well-placed and well-timed conservation activities and gives experienced Zuni farmers a measure of control over a relatively unstable landform. This situation may partly underlie a sense of responsibility for the land that is inherent in Zuni culture: neglect of conservation activities can have rapid and drastic impacts on soil productivity and, by extension, important hydrological and ecological functions of alluvial fans.

LOCAL KNOWLEDGE

Local knowledge and indigenous agricultural systems can provide valuable foundations for sustainability as developing economies scale up to join modern world markets (Bomke et al., 1994). But understanding how small-scale market- or subsistence-oriented agricultural systems work in complex local settings requires careful research combining sociology, ethnoscience, and agroecology (Norton et al., 1998). Even with careful study, subtleties inherent in highly specialized systems can be elusive because of faulty assumptions, distrust, or lack of clearly stated advantages for cooperation.

The complex interplay of environment, culture, and agriculture can be difficult for scientists from western academic traditions to understand (Kloppenburg, 1991), especially in highly variable, disturbance-driven environments like those of many semiarid regions. Such complexity too often causes well-intentioned scientists or development agents to assume locals behave irrationally with respect to ecology (Pawluk et al., 1991). Such assumptions substitute for and prevent real understanding as they deny

well-meaning scientists of valuable ecological insights and local people out of potentially relevant, appropriate, and useful technological information. Improved comprehension of complex natural systems suggests that scientists' failure to understand local environmental knowledge results not only from sociological (or social) ineptness, but also from fundamental errors in scientific interpretation of the environment itself (Ellis and Swift, 1988).

Recent views of ecosystem processes emphasize external environmental factors such as disturbance (e.g., fire, storm, flood), short-term climate change (e.g., drought), and local variation as drivers of ecosystem structure, function, and change (Botkin, 1990; Pieper, 1994; Seastedt and Knapp, 1993; Westoby et al., 1989). These concepts could open the door to alternative definitions of sustainability (Ellis et al., 1993) and redeem local knowledge that seemed irrational under the theories that guided ecology for most of the 20th century (Brookfield and Padoch, 1994; Fujisaka, 1997; Peet and Watts, 1996). However, bridging the gap between accepted scientifically-derived concepts and local knowledge derived from long-term livelihoods in specific environments remains a challenge.

My work at Zuni included facilitating what I believe evolved into genuine collaboration between a team of research soil and ecological scientists and the farmers running ZSAP. This experience may offer some transferable methods for achieving real understanding between scientists and local agriculturists. In this case, scientists and local farmers were each so deeply indoctrinated in their own ways of knowing about the Zuni farming system that they assumed they had a common understanding of its function. Profound, unanticipated differences emerged when the research team worked Zuni

farmers to construct and manage a controlled scientific study of a local farming system. While each situation is unique, this aspect of the research – collaborative hands-on labor to investigate an exogenous perception of a local system – may provide insights for meaningful interactions in other research and/or development settings.

ZUNI FARMING ENVIRONMENT AND HISTORY

Zuni is an agricultural tribe of the Southwestern U.S. Pueblo culture; one of 19 Native American groups known for dryland farming expertise, distinctive architecture, and unique cultural traditions (Ferguson, 1996). The Zuni Indian Reservation lies in the heart of the Zuni's original homeland, at around 2000 m elevation in the southeastern Colorado Plateau province (Ferguson and Hart, 1985). High, sandstone-capped mesas and broad alluvial valleys characterize the Zuni landscape. The growing season ranges from 90 to 120 days, precipitation averages about 300mm, and evaporation about 1280mm (Thomas et al., 1997; Western Regional Climate Center, 2000a), though the climate is highly variable within a distinct seasonal pattern, receiving as much as 70 percent of annual rainfall in July, August, and September.

Zuni subsistence relied heavily on agriculture for over two millennia (Damp and Kendrick, 2000; Kintigh, 1985). Corn grown in non-irrigated fields was a staple, as noted by the Spanish Conquistador Coronado in his report to the Viceroy Mendoza in 1540: *"(the people) are all well nurtured and condicioned... The victuals which the people of this countrey have, is Maiz, whereof they have great store..."* (Cushing, 1920). Pueblo archaeology shows nearly constant agricultural transition as populations grew, new crops and farming methods were introduced, and environmental conditions fluctuated (Cordell, 1984; Hack, 1942; Plog, 1997). Until the mid 19^{th} century, when United States

occupation began, agriculture was built upon transgenerational local knowledge of the unique climate and dynamic landscape. Large U.S. sponsored irrigation projects introduced in the early 20th century resulted in major changes that disregarded and discredited local knowledge and traditional farming systems (Cleveland et al., 1995). Completion of the large dams accompanied re-allotment of irrigable lands without regard to ancient, clan-based tenure systems. After 1900 combined population depletion, rapid sedimentation of irrigation reservoirs, and insidious land disputes from forced re-allotment precipitated steady decline in agriculture and transition to dependency. Nevertheless, even now traditional crops remain vital to religious traditions and cultural identity, although unique farming expertise continues to disappear due to modern pressures.

The Zuni Sustainable Agriculture Project

The 1990 court settlement in the Zuni Tribe vs. the United States over mismanagement of federal trust lands (the Zuni Reservation) funded Zuni-controlled programs to restore the basis for a natural resource economy (Hart, 1995). ZSAP became one component of the effort and was partly funded by the Ford Foundation. ZSAP is run by a group of traditional Zunis who, in their early 50's, may be representatives of the last generation to grow up in traditional, subsistence-oriented, farming and herding lifestyles. Their goal is to revitalize farming on the reservation, first for its cultural values and, in the long run, as an economic option for Zuni people. Their methods address local control of irrigation systems, helping settle land disputes, and acquiring farming equipment for a rental program. ZSAP leaders see their most important role as reawakening Zuni people, especially younger generations, to their agricultural heritage, reminding them that

planting seeds each spring is part of being Zuni. While hunger and abject poverty are not as devastating as in many developing countries, over a century of dependence and cultural repression has culminated in widespread diabetes, depression, alcoholism, and suicide, today's main killers of Zuni people. ZSAP's leaders directly connect these problems with separation of people from their agricultural heritage. An underlying component of ZSAP is to reestablish the credibility of Zuni knowledge in the minds of tribal and government decision makers and, perhaps most significantly, in the minds of the Zuni people themselves.

AGROECOLOGICAL RESEARCH AT ZUNI

Preliminary Studies

Runoff farming is an important component of historic and prehistoric Southwestern Native American agriculture (Kintigh, 1985; Nabhan, 1984). Authors typically describe runoff farming as a type of water harvesting where farmers capture and divert ephemeral stormwater flows to make up moisture and nutrient deficits imposed by the semiarid climate (Cushing, 1920; Hack, 1942; Nabhan, 1984). Runoff farming and other water harvesting schemes have been recognized, described, and developed in many agricultural systems of dry lands (Bryan, 1929; Critchley and Siegert, 1991; Evenari et al., 1982; Frasier, 1980; Gardner and Hubbell, 1942; Kowsar, 1991; Nabhan, 1981; Neimeijer, 1993; Tabor, 1992; Tabor, 1995). Most descriptions of Native American runoff farming describe a scenario where timely ephemeral flows and specialized water management techniques supplement depleted soil moisture and fertility as crops approach late summer rapid growth periods; a vision of runoff from uplands as irrigation and fertilizer for crops planted in low landscape positions.

Fields of the Zuni Indian Reservation offer unique opportunities to evaluate very long-term effects of agriculture on soils. Excellent historic documentation and archaeological records allow verification of fields having been farmed at least intermittently for over 1000 years, some of the oldest documented fields in North America. As such, Zuni fields offer a look at time intervals much longer than most documented farming systems (Sandor and Eash, 1991). This longevity, along with documentation that traditional farming includes no fertility-enhancing inputs, led scientists to propose a set of hypotheses about how soil productivity is sustained by watershed contributions of moisture and fertility – that ephemeral stream flow acts essentially as irrigation and fertilizer to alleviate immediate moisture and nutrient deficits for crop growth.

Dr. Jonathan Sandor, Iowa State University (ISU), began reconnaissance studies of how soils react to long-term agriculture at Zuni in 1990. Roman Pawluk, an ISU graduate student working under Dr. Sandor, began his study of Zuni soil terms and agricultural knowledge in 1991 (Pawluk, 1995). I began working with Dr. Sandor in 1993 to explore linkages between sustained soil productivity and watershed processes as part of my M.S. from ISU. These initial studies began as a loose collaboration with the Zuni Archaeology Program, independent of Tribal initiatives for ecological restoration and agricultural revitalization, and did not include collaboration with local people. The Tribe was just beginning development of those priorities.

As such, we interpreted results of these initial studies completely in the context of anthropological, ecological, and archaeological literature, without input from local people. The conclusions from our studies, which supported hypotheses that would be

explored in subsequent National Science Foundation (NSF) research include:

1. cultivated soils in active alluvial zones are altered, but not degraded relative to uncultivated controls, while cultivated soils of areas cut off from flooding or on erodible landforms are depleted (Norton, 1996; Norton et al., in press);
2. erodibility of backslope positions with relatively shallow, clayey argillic horizons, little ground cover vegetation, and relatively thick pinyon-juniper forests and associated litter suggests potential for movement of water, sediment, and organic matter toward fields during thunderstorm events (Norton, 1996);
3. farmers value alluvial sediment and fresh, sandy deposits (Norton et al., 1998; Pawluk, 1995).

Nation Science Foundation Research and My Dissertation

In the context of runoff farming literature and the soil attributes we discerned, these conclusions suggest that watershed materials conveyed to fields in ephemeral stormwater flows likely supported long-term agricultural sustainability indicated by soil attributes. With the information available, and in the context of current understanding of the farming system, Zuni farmers' recognition of the value of fluvial processes and transported materials seemed to support the hypothesis that watershed contributions alleviate immediate moisture and nutrient deficits for crop growth. These initial results, which later collaboration with local farmers would redefine, led to the more comprehensive study of which my dissertation is a part.

The expanded study began in 1996 and consisted of three scientific objectives designed by an interdisciplinary research team and two objectives designed in collaboration with a group of Zuni farmers and natural resource managers. The latter

focused on knowledge exchange and interpreting scientific results to reflect Tribal land use priorities. This approach helped to develop relationships between the research team and traditional Zuni people that led eventually to valuable understanding of each other's perceptions. However, farmers were not directly involved in designing scientific objectives, partly because we assumed that we shared a common understanding of basic operation of the farming system; ours from the literature and theirs from experience. For the same reason, our Zuni collaborators did not scrutinize our scientific approach; they assumed that our basic understanding of how their agricultural system works was similar to theirs. This led to significant misunderstandings that required a great deal of effort to address and that deepened our and Zuni understandings of differences in perspectives. The five NSF research objectives included (references refer to preliminary presentations of results):

1. Determine effects of long-term Zuni runoff agriculture on soil morphology, organic matter, and nutrients: An extension of the soil productivity investigations (Havener et al., 1999a; Homburg, 2000; Thomas and White, 1999a).
2. Define ecosystem structure and function as they affect runoff inputs to maize fields: An extension of the watershed soil-plant-landform and runoff-erosion investigations (Havener et al., 1999b; Laahty and Norton, 1999; Norton et al., 1999; Thomas and White, 1999b; White and Thomas, 1999) and present here in chapters 2, 3, and 4).
3. Evaluate effects of watershed moisture and nutrient inputs on crop productivity: In-field controlled investigations of components of the "irrigation and fertilizer" hypothesis, including runoff water and runoff water plus sediment, against rain only, irrigated, and fertilized treatments (Kuratomi et al., 1999; Muenchrath et al., 1999).

4. Develop criteria for identifying potential use of runoff agriculture in arid and semiarid lands: Extrapolate the results for use in current priorities for land use, restoration, and development at Zuni and elsewhere.
5. Develop a technological exchange between the Zuni Tribe and the research team: Included practical and training components as well as exchange of more abstract concepts and perceptions (Norton and Sandor, 1997; Norton and Laahty, 1999; Norton et al., 1998) and presented here in chapter 5).

By the time we developed these objectives Tribal authorities had defined priorities such that any research must show direct benefits to Zuni people. ZSAP's leaders agreed to support the NSF project and collaborate with us because they felt scientific study could help to validate their traditional farming system. The leaders served on our "Zuni Advisory Committee" with whom I met almost daily during field seasons. ZSAP's leaders took the decision to support the project very seriously because, in the eyes of Zuni people whose trust and respect they sought, the researchers' actions would reflect directly on them. They understood very well that this created a responsibility to see that farming system was represented accurately. For the researchers collaboration with traditional people presented valuable opportunities for learning about farming methods and local perceptions about climate and agriculture. This "technological exchange" became integral to the research.

The Zuni Advisory Committee's knowledge of local people, places, and farming methods were invaluable. But when the Zuni helped establish and manage the crop productivity investigation (objective 3) they began to realize that the researchers' perceptions of their farming system were very different from their own. It took hands-on

labor, growing Zuni corn under what a scientific perception of the traditional system, to transcend language and cultural barriers that neither the local Zuni advisors nor the researchers were aware existed. When application of the treatments began, it became clear to the Zuni that from their perspective we were asking the wrong questions. Ensuing discussions became contentious at times as we struggled to explain and understand one anothers' perceptions and motivations. The real learning that resulted from these unforeseen differences between the scientific understanding, gained from the literature and short-term observations, and their understanding, from experience and transgenerational knowledge, brought fundamental changes to our basic research assumptions, took the research in new and valuable directions, and may create outcomes far more valuable to restoration and development efforts at Zuni as well as to scientific knowledge of Native American agroecology in general.

Specifically, the hypothesis that we perceived silty water is a type of immediate fertilizer became clear to the Zuni only after runoff and sediment captured from artificial catchments above the corn productivity study was applied to selected plots, and fertilizer and irrigation water was applied to other plots. As they arduously explained, Zuni do not view silty runoff water as beneficial to the current crop and in fact see intentional application of silty sediment over sandy loam soils as detrimental, plugging pores and ruining hydrological characteristics that drive selection of field locations. Interestingly, young Zuni employees working were skeptical of applying silt to corn plants, though they could not explain precisely why, only that it was "killing their sisters" or that the researchers "only grow corn to kill it." As I worked closely with the ZSAP leaders to address their concerns I began to better understand their perspective and several pieces of

incongruous information began to fall into place. For instance, there had been problems applying treatments; soils were often too wet for several days after runoff events, suggesting that in a natural situation runoff may not have infiltrated the soil; silt accumulated over the soil as runoff was applied, slowing infiltration so only a fraction of the planned-for runoff could be applied. Also, the rain-only plots, as well as farmers' fields that clearly received no runoff, actually yielded quite well. Farmers' tendency to focus on soil characteristics rather than diverting runoff water, the value they place on sandy, alluvial soils, and their insistence on calling the system "rainfed" rather than "runoff" farming all began to make more sense.

Insights from the farmers enabled reconsideration of some the scientific perspectives and formation of a different paradigm from which to evaluate research findings. At this time, I began to conceive of an alternative model more analogous to floodplain farming than to water harvesting (presented in Chapter 1).

The work reported in this dissertation contributes to the larger study of soil, crop and ecosystem aspects of the Zuni farming system (Sandor et al., in press). This NSF sponsored work began with the premise of a "technological exchange" where collaboration between the research team and local Zuni people would result in learning for both. The research team did not anticipate, however, that collaborative fieldwork with traditional Zuni farmers would fundamentally change our perception of a farming system that we thought had been accurately described over 100 years ago. Fortunately, our research plan incorporated enough flexibility to pursue new concepts that emerged from our collaboration. For me, the ability to truly listen and change the course of our research resulted in real learning and, I believe, in results more valuable to both the

researchers and to the Zuni people than they otherwise would have been.

The first chapter explores the difference in perception and describes an alternative, more complete view of Zuni rain fed farming that is of potential value to contemporary conservation and restoration efforts in semiarid landscapes. Chapters two, three, and four analyze linked hydrological, soil, and ecological processes in the hillslope (source), fluvial (transport), and alluvial fan components of the agroecosystem. Chapter 5 describes and evaluates a traditional approach to conserving and restoring ephemeral stream systems very difficult to manage by conventional engineering approaches.

THE VALUE OF COLLABORATIVE RESEARCH

I believe the alternative model revealed to us by Zuni farmers represents a conceptual departure from many past descriptions of Native American runoff agriculture. Though this fascinating and diverse farming system has been studied for many years by many researchers, this study may be the first in which locals played an active role in critiquing an in-situ investigation of the accepted scientific model. This interaction allowed insights not available to earlier authors who based their findings on observations filtered through their own experiences and culturally based perceptions. These earlier authors' perceptions may in part have been shaped by a desire to "systemize" the farming knowledge as water and nutrient harvesting so well defined in other parts of the world.

As one of the ZSAP leaders succinctly explained, "you scientists keep trying to describe our farming *system*; we don't have any system because everything changes every year!" This proclamation uttered in a moment of frustration underscores the alternative perception of Zuni farmers. Successfully drawing a livelihood from a highly variable, in some respects unpredictable, environment requires dynamic approaches that

draw on a long history of interaction that may be more opportunistic than systematic. Farmers apply combinations of innovation and indigenous knowledge to ever-changing situations. These concepts define an alternative notion of sustainability that may be difficult for those from the western scientific tradition to grasp, but may be crucially important to understanding complex, changing environments where humans have long played an essential role.

I hope the studies reported in this dissertation help Zuni people regain rights to apply their own knowledge to environmental restoration and agricultural revitalization on their reservation. I also hope the results reported here provide an example of how genuine collaboration with local expert farmers, though difficult, can make research more accurate, meaningful, and relevant. Finally, I hope principles of semiarid agroecology and adaptive management approaches that I discuss contribute to understanding the types of alternative paradigms that must prevail as global climate change moves more of the Earth toward a Zuni-like environment: drier, more variable conditions and where small stimuli can have large and unpredictable impacts (Goudie, 1994).

Chapter 1: Zuni rain fed agriculture and environmental change

INTRODUCTION

Rapid and increasing rates of environmental change create a need for ever more ecological information on which to base conservation policy and practice (Ford and Martinez, 2000). Renewed interest in traditional ecological knowledge as complementary ways of knowing about nature (Berkes et al., 2000; Pawluk et al., 1991) promises to both improve and expand our understanding of complex and changing ecosystems. But the value of such knowledge to contemporary issues relies on its accurate interpretation. Collaboration with local people whose lives and culture intertwine with complex ecosystems can yield more and better information, contribute to conservation of biodiversity, and reveal development paradigms with inherent sustainability (Ellis and Swift, 1988; Winklerprins, 1999). Contributions from traditional knowledge are often unanticipated because local people have perspectives only possible through prolonged, intimate contact with particular environments (Huntington, 2000; Kloppenburg, 1991; Norton et al., in press). Differing cultural and ecological viewpoints between scientists and local people make accurate understanding difficult, however; and misunderstandings can negate the value of local knowledge (Scoones, 1999; Sillitoe, 1998). Interpretation of local perspectives of and interactions with the environment is usually the realm of the social sciences, but anthropologists or sociologists may miss subtle ecological meaning at least as easily as ecologists or soil scientists miss social nuances. Natural scientists and traditional local people often share life-long commitment to understanding the natural world that can bring conversations to higher levels.

Traditional rainfed farming by the Zuni represents traditional ecological knowledge with applications for ecological conservation and sustainable agriculture (Norton and Sandor, 1997). Collaboration with local farmers, in the context of improved understandings of environmental variability, could improve simplistic interpretations as water harvesting or runoff irrigation (Damp and Kendrick, 2000; Hack, 1942; Kintigh, 1985) that obscure value to contemporary problems. This chapter reports an effort to advance understanding of Zuni rain fed farming with: 1) descriptions by Zuni farmers interviewed during this and previous studies; 2) review of hydrological context as revealed by climatic and watershed data; and 3) investigation of parallels among social and environmental changes that suggest declining agriculture contributes to accelerated erosion.

Study of accelerated arroyo cutting in the Southwest recently turned to complex interactions rather than singular causes (Bull, 1997; Elliot et al., 1999). The long and contentious debate that led to this point helped advance understanding of complex, unstable semiarid environments. However, whether arroyo incision is inevitable episodic behavior in fluvial systems near geomorphic thresholds (Schumm et al., 1984), reaction to severe climatic perturbation (Balling and Wells, 1990), or response to overgrazing, road construction, timber harvest, or other contemporary land use activities (Cooke and Reeves, 1976), the result destroys connections between erodible uplands and depositional valley floors. Continuously incised arroyos diminish water storage and flood mitigation functions of alluvial fans and flood plains, reduce ecological diversity and productivity for livestock, wildlife, and agriculture, drain alluvial aquifers that feed springs and riparian areas, and contribute sediment and biological oxygen demand to downstream

waters (Bull, 1997; Cole et al., 1990; Schumm, 1999). As erosion continues to disrupt both terrestrial and aquatic ecosystems, effective and economically feasible solutions remain elusive (Briggs et al., 1994; Goodwin et al., 1997).

People who depend on resources easily lost to erosion make no distinctions about cause but simply intervene in the most effective way possible to protect their means of survival. Agricultural traditions of Native American groups in Southwest U.S., including the Zuni, value hydrologic properties of alluvial deposits (Ford, 1985; Nabhan, 1984; Pawluk, 1995). Practices for maintaining depositional regimes on highly dynamic alluvial fans may be central to non-irrigated farming by these groups (Bull, 1997) and may represent effective means of preventing or restoring arroyo cutting.

Past studies begin with the assumption that corn (*Zea mays*) cannot be grown in the Southwest without supplemental moisture and that rainfall events that do not generate runoff are of no value for crop production (Hack, 1942; Kintigh, 1985). These assumptions are based on average rainfall and optimal crop water requirements derived from conventional irrigated agriculture. Following this line of reasoning, farming techniques must rely on runoff for supplemental moisture. This approach places Zuni runoff farming in the realm of water harvesting systems used by cultures in Sudan, Iran, the Negev, and others (Evenari et al., 1982; Kowsar, 1991; Niemeijer, 1998; Tabor, 1995) and precludes other perspectives without ever referring to local practices or knowledge.

In contrast, the few published interviews show that Native American farmers value hydrological properties of fresh flood deposits more than runoff water (Ford, 1985; Pawluk, 1995), a fundamental difference that suggests emphasis on control of sediment

rather than water. Local farmers rarely have a voice in studies of Southwestern landscape dynamics or even native farming. This may be partly because their view, forged by survival in a semiarid environment where "normal" rainfall can vary from arid to subhumid, has heretofore seemed irrational to a science steeped in notions of equilibrium. With broad acceptance of unpredictability and complexity in natural systems (Botkin, 1990), there is now opportunity (responsibility, perhaps) to interpret traditional ecological knowledge from a new, disequilibrial perspective (Peet & Watts, 1996).

Better understanding of how traditional land use practices interact with unstable landscapes can provide not only effective techniques (Bocco, 1991), but also adaptive decision-making processes (Berkes et al., 2000; Fujisaka, 1997). Concepts arising from dynamic agroecosystems differ with respect to space and time from conventional notions of sustainability. They hinge upon flexibility and iterative decision-making, much like modern theories of range ecology research and management (Westoby et al., 1989). Such alternative perspectives may be valuable at a time when increasing variability – and unpredictability – is forecast almost everywhere.

Local Knowledge and Ecological Complexity

Bull (1997) describes the depositional reaches of ephemeral streams as chaotic and unpredictable because stream power thresholds respond rapidly to runoff. The nature of geomorphic response (aggradation or incision) can be difficult to predict because runoff magnitude and frequency are products of precipitation and landscape factors (Bull, 1987; Graf, 1988; Schumm et al., 1984). Recognition and acceptance of this type of complexity in the natural world has influenced nearly every environmental science during the last 20 to 30 years, from basic atmospheric studies to predictions of wildlife

populations (Botkin, 1990). Resulting ecological theory discards centuries of western scientific thought based on notions of a "static world," (McIntosh, 1987) and may offer a degree of redemption for many "non-science" viewpoints long dismissed as irrational (Peet and Watts, 1996; Scoones, 1999). "New ecology" is changing views of some local knowledge systems, especially in highly variable, "disequilibrial" environments (Ellis et al., 1993; Nugent, 1991).

Indigenous agricultural systems in highly variable, resource poor areas differ significantly from systems established on rich soils in more stable ecosystems. Interestingly, indigenous systems developed on fertile soils or in areas with predictable moisture and growing temperatures are considered models of fascinating indigenous ingenuity. Examples of such include irrigated terraces of the semiarid Andes (Sandor and Furbee, 1996), rice terraces of the humid tropics (Siebert and Belsky, 1990), or water harvesting in the Negev (Evenari et al., 1982). Indigenous knowledge in ecosystems with poor soils, unreliable precipitation, and unpredictable productivity (i.e., shifting cultivation, nomadic herding, and alluvial fan farming) – have long been seen as primitive methods barely viewed as agriculture (Ellis and Swift, 1988; Norton et al., in press; Nugent, 1991). The rationality of these systems is emerging, however, as they are reconsidered in light of disequilibrial ecology.

Studies of range utilization by native herders in Kenya (Ellis et al., 1993) show that, in ecosystems where standard deviation among annual precipitation records approaches 30 percent of the mean (coefficient of variation, or CV = 0.30), long-term productivity may be better defined in terms of variability than measures of the average. Applied to native grazing strategies in highly variable semiarid regions, this concept

suggests that flexibility inherent in nomadic lifestyles, swapping grazing access among groups, opportunism, and other practices long thought to be detrimental and irrational may in fact be appropriate. Unfortunately, these observations came after decades of failed allotment policies based on notions of average carrying-capacity (Ellis and Swift, 1988).

Shifting cultivation in the humid tropics is another case of shifting views of indigenous practices. Such systems, often referred to as "slash and burn," are ubiquitous in tropical forests, though in many different forms, and were thought to be destructive and inefficient for many decades (Redford and Padoch, 1992). Improved understanding of agricultural restraints in tropical forests, particularly in very old soils depleted by millennia of leaching and rapid biological respiration (Weischet and Caviedes, 1993), changes perspectives of shifting cultivation. In some cases, shifting cultivation is now viewed as sophisticated ecological succession control where the ecosystem is "systematically manipulated and ... to a significant degree, the subservient domain of the social system" (Nugent, 1991:145).

Relatively recent comprehension of the role of fire in forest and grassland ecosystems in the western and midwestern U.S., and the possibility that, to large degree, those landscapes look as they do because of Native Americans' use of fire (Arno et al., 1995), presents another case where the ecosystem may be, "to a significant degree, the subservient domain of the social system."

In the southwestern United States, a great deal of work on rapid landscape change reveals the complexity of what has become known as "the arroyo problem." In general, extreme downcutting started in the late 19th century and is documented across the southwest. Scientists historically associate this apparently "pan-southwest" degradation

with intensified land use – particularly grazing (Bryan, 1925; Hack, 1942; Thornthwaite et al., 1942). More recent evaluations, based on modern understandings of geomorphic change and decades of climatic data, focus on long-term climate change, short-term climatic perturbation, and fluvial systems near threshold conditions as the impetus for downcutting (Balling and Wells, 1990; McFadden and McAuliffe, 1997; Wells, 1987). Closer examination of the many local studies over the last century indicates that the "arroyo problem" is not regionally synchronized; nor is any one cause or combination of causes responsible. Rather, each downcutting arroyo system has a unique history, time of onset, set of causal factors, and stabilization scenario (Cooke and Reeves, 1976; Elliot et al., 1999; Graf, 1988). Indeed, many systems remain inexplicably unincised, with discontinuous channels or broad, aggrading alluvial plains (Bull, 1997).

Though imposed on this same landscape position, traditional farming of the Zuni, Hopi, Navajo, Rio Grande Pueblos, Papago, and others (Hack, 1942; Homburg, 2000; Nabhan, 1984; Sandor et al., 1990) is disregarded in studies of arroyo and alluvial fan dynamics. Improved understanding of the landscapes they utilize offers opportunities for real communication with local farmers whose system continues to be described as water-harvesting where farmers are victims as down-cutting places runoff beyond their reach. As such, incision is cited as a cause for agricultural decline and failure, partly responsible for documented depopulation and migration in prehistoric times (Plog, 1997) and social change in recent history (Cleveland et al., 1995; Hack, 1942). However, Zuni farmers suggest that they do not consider themselves victims of environmental change, but active manipulators of fluvial processes who have a definite role in how their landscapes look and behave.

Local people can have unique and specialized perspectives crucial to understanding complex ecosystems, especially those embedded in complicated social systems. But those perspectives may differ significantly from researchers' experiences and education. The rural sociologist Jack Kloppenburg (1991) provides the premise of the work reported in this chapter:

> ... intimate sustained engagement with their means of production endow farmers not only with a deep knowledge of local particularities, but also with a holistic and systematic understanding of local agriculture that reductionist science cannot easily approximate. (Kloppenburg, 1991).

RESEARCH APPROACH

My goal is to describe agroecological aspects of the farming system that may be relevant to contemporary environmental problems. The following four steps were employed to identify and confirm Zuni priorities for successful rain fed farming, to investigate the feasibility of water harvesting assumptions in the context of Zuni climate and hydrology, and to explore the possibility that Zuni farming conserves soil resources:

1. Collaborative field work and non-structured interviews with a group of Zuni farmers involved in collaborative agroecological research;
2. A field survey of randomly selected fields and landuser interviews to verify concepts identified in step 1;
3. Analysis of precipitation patterns and hydrology in small agricultural watersheds to verify concepts from the interviews;
4. Investigation of parallel socio-economic, demographic, and environmental changes to explore circumstantial links between declines in land stewardship and accelerated erosion.

Collaborative Field Work and Non-Structured Interviews

I collaborated with of a group of four traditional farmers as the field research coordinator for a four-year multi-disciplinary study of agroecological aspects of non-irrigated farming (Sandor et al., in press). Local knowledge and environmental perspectives were sought during informal, non-structured interviews and collaborative field work (Huntington, 2000) recorded via note-taking. Unanticipated consequences of this collaboration surfaced rapidly as the farmers assisted researchers testing hypotheses about runoff irrigation. The farmers recognized that the hypotheses came from a perspective very different from their own. As community leaders in agriculture (they were also leaders of a grassroots sustainable agriculture project funded by the Ford Foundation), they perceived responsibility to see that the research portrayed Zuni farming accurately. This motivated group and one-to-one conversations (essentially two-way semi-directive interviews) where each side presented their principles and tried to understand the other (Norton et al., 1998). Though no prescribed lists of topics or questions were used, the research hypotheses with which we were all familiar provided this direction.

Field Survey and Land User Interviews

In order to explore concepts shared by the Zuni research collaborators, I randomly selected non-irrigated fields, documented land use history, and interviewed land users. As a field history approach, this protocol also provided some information on soils, land use patterns, and changes over the 10 years from 1988 to 1998. Selection was based on the work of Graham (1990) who identified 76 non-irrigated fields under cultivation in 1988. I randomly selected one third (25) of these fields, made observations of land use,

soils, and landscape setting, and then interviewed land users that could be located about their use of that particular field and about their approach to non-irrigated farming in general. Interviews followed an informal, semi-directive format (Huntington, 2000) where a prepared list of topics was discussed at the home or in the field of the interviewee. The discussions were tape-recorded by permission, or were recorded via note-taking. An interpreter was hired for several interviews with older people uncomfortable speaking English. In these cases, I carefully reviewed the notes or tape with the interpreter immediately following the interview.

Hydrological Context of Traditional Zuni Knowledge

Agroecological concepts presented during the interviews, as well as those of the conventional scientific "water harvesting" approach, were explored in the context of precipitation patterns and watershed hydrology on the Zuni Reservation. Precipitation analysis relied on 1949-2000 records available from the Western Regional Climate Center (Western Regional Climate Center, 2000a), precipitation duration-frequency maps (Western Regional Climate Center, 2000b), and 1895-1985 daily rainfall records for the Zuni region compiled and summarized by Balling and Wells (1990). In order to explore the feasibility of "runoff irrigation" in the Zuni environment, I calculated average recurrence intervals for exceedence of flow thresholds (when soil and channel storage is overcome and ephemeral stream flow begins) by: 1) analyses with USGS regression equations (Thomas et al., 1997) to estimate peak flow rates for 2, 5, 10, and 25 year recurrence interval flows in five small agricultural watersheds (the same watersheds studied for other research reported in this dissertation); 2) regression analyses of those flow values to estimate recurrence interval of the 0 m^3s^{-1} event (ephemeral flow

initiation).

I also applied a distributed watershed yield model (Natural Resource Conservation Service curve number method; McDougal et al., 1985) to the same five watersheds, subtracting for transmission losses (Lane, 1990), for various precipitation events. Soil and cover information for determining curve numbers came from data collected in studies reported in chapters 2, 3, 4, and 5. Hydraulic conductivity (K) values for estimating transmission losses in the sandy channels with Lane's equation (1990) were estimated at 10^{-3} cm s^{-1} based on particle size of channel deposits by the relationship $K = d_{10}^2$; where K is hydraulic conductivity (cm s^{-1}) and d_{10} is grain diameter (mm) larger than 10 percent of the particles (Personal communication, Mark Ankeny, 2000). In the sandy ephemeral channels of the Zuni Reservation, $d_{10} = 0.125$ mm or very fine sand, approximately.

RESULTS AND DISCUSSION

Field Surveys and Interviews

Results of the non-irrigated field survey underscore both rapid erosion of Zuni agricultural knowledge and its ongoing innovation. Of the 25 fields selected and analyzed, I judged eight to be located where runoff was important to their operation while 17 are exclusively rainfed (Table 1–1). Thirteen individual land users were positively identified for 18 of the selected fields. Users of the remaining seven fields could not be identified or confirmed in the timeframe of the study. These fields were small plots and could not be readily identified by our Zuni research collaborators, whose business over the last six years has been to map fields and identify owners. Of the 13

individual land users identified, four were deceased. Two of the deceased farmers accounted for six of the 25 fields selected from the 1988 inventory and the Zuni collaborators remembered all four as devoted and knowledgeable farmers.

Table 1–1. Summary of results of randomly selected non-irrigated farm fields and interviews, 1998.

Fld No.*	Ha cultivated	Farming Area	Land user	Primary Farmer?	Gender	Age	Interview	Runoff or rainfed?	Other Fields?	Active Erosion Control**	"Expert" Farmer?+
185	0	Mullen	B.B.	Y	M	70	Yes	rainfed	Yes	Yes	Yes
124	0	Pescado	D.Q.	Y	M	35	Yes	runoff	Yes	Yes	Yes
96	0	Great Kivas	H.J.	Y	M	70	Yes	runoff	Yes	No	No
32	0	Zuni	I.G.	N	F	68	Yes	runoff	Yes	No	No
71	0	Galestina	L.L.	N	F	75	Yes	rainfed	Yes	No	No
66	0	Mullen	P.N.	Y	M	65	Yes	rainfed	no++	Yes	Yes
132	1.7	Pescado	P.P.	Y	M	68	Yes	runoff	no	No	No
188	0.2	Horsehead Cyn	Z.W.	Y	F	32	Yes	rainfed	Yes	No	No
152	0	Nutria	B.L.	Y	M		no[1]	rainfed			Yes
180	0	Dowa Yalanne	B.L.	Y	M		no[1]	runoff			Yes
76	0	Galestina	S.K.	Y	M		no[1]	rainfed			Yes
148	0	Nutria	S.K.	Y	M		no[1]	rainfed			Yes
158	0	Nutria	S.K.	Y	M		no[1]	runoff			Yes
159	0	Nutria	S.K.	Y	M		no[1]	runoff			Yes
73	0	Galestina	S.S.	Y	M		no[1]	rainfed			Yes
84	0	Galestina	G.T.	Y	M		no[2]	rainfed			Yes
130	0	Pescado	G.T.	Y	M		no[2]	rainfed			Yes
8	0	Zuni	?				no[3]	rainfed			
44	0	Zuni	?				no[3]	rainfed			
47	0.3	Zuni	?				no[3]	rainfed			
68	0	Galestina	?				no[3]	rainfed			
91	0	Zuni	?				no[3]	rainfed			
120	0.4	Pescado	?				no[3]	rainfed			
154	0	Nutria	?				no[3]	runoff			

* from Graham, 1990.
** "Yes" indicates farmer was enthusiastic and knowledgeable about erosion control techniques.
\+ "Yes" indicates that farming was clearly central to the interviewee's life and activities; they talked at length about their techniques, experiences, and innovations as well as those of others; "no" indicates that interviewee was not as confident and forthcoming with farming knowledge, relied on someone else to direct farming efforts, and/or they farm for personal reasons and not employment. "Expert" status of farmers not interviewed is based on opinions of key informants. L.L. is respected as an expert gardener.
++ P.N. is an active farmer with several fields who was prevented from planting in 1998.
1 Deceased.
2 Moved out of state.
3 Could not be identified or contacted.

Of the seven farmers interviewed, three were "expert" farmers who controlled multiple fields, owned tractors and tillage equipment, and confidently discussed soil, water, plant, and other agricultural issues and decision-making processes. Each of the three women interviewed focused primarily on hand-irrigated gardening and did not claim expertise about rainfed farming. Of the last two farmers, neither owned farming equipment and each had only one field that they planted to corn each year. One claimed a strong, life-long farming background but was reluctant to discuss corn with an outsider, partly because of its religious significance and partly because of a language barrier (use of an interpreter was initiated after this interview). The other had worked off-reservation for the U.S. Forest Service and Bureau of Indian Affairs for many years and started growing corn after he retired and returned to Zuni. The three "expert" farmers enthusiastically discussed erosion control techniques as an integral part of non-irrigated farming while none of the five others claimed any knowledge of erosion control. All the less active farmers felt strongly that crops raised in their fields could not be sold but only used for religious purposes, shared with family, or consumed. The three "experts" generally had a more economic approach to farming but concurred that, although very important, non-irrigated farming is more a cultural-religious activity than an economic one; though they all thought that corn and other crops could be sold once everyone in Zuni had all they needed.

How Zuni Farmers Describe Rain Fed Farming

Rain fed farming as described by farmers contrasts with the system envisioned by scientific descriptions of "runoff" agriculture in that, while moderate flows can boost

crop production, runoff is too undependable for reliable irrigation and can be more destructive than beneficial. In contrast to water-harvesting assumptions, farmers clearly value the frequent minor rains that do not produce runoff. Protecting and enhancing loamy flood deposits that rapidly absorb minor rains is a motivating factor behind "water control" efforts. In general, the magnitude of ephemeral flows are considered to be too variable for labor-intensive construction of "irrigation systems." Previous authors discuss erosion control as a beneficial side-effect of water spreading, while farmers clearly consider it the main objective.

All the farmers believe erosion results from lack of agricultural use. Remarks of the three randomly selected "expert" farmers, others interviewed over the course of the four-year study, and the four Zuni research collaborators generally concur about the basic operation of rainfed farming at Zuni. Farmers quoted by other researchers also concur, although interpretations of those quotes may differ from that presented here. Observations of Stewart (1940) about drastic erosion on a Zuni farming area abandoned after it was removed from reservation holdings support the notion of farming as effective conservation: "(Severe erosion in Bosson Wash) shows clearly that land under flood-water flow must be wisely and continuously used if it is to be preserved" (Stewart, 1940:337).

According to farmers, the location of rainfed fields is based on soil properties, and sandy or loamy soils are preferred. Farmers consistently point out that sandy soils are the best for rainfed corn because they soak up rain rapidly. Several farmers noted that clay stays moist longer but can cause erosion or ponding problems. Preference for sandy/loamy soils is confirmed in studies of Zuni soil terminology by Pawluk (1995) and

Ford (1985). These types of highly permeable soils are apparently capable of producing crops with rain alone in many years. Well sorted, fresh flood deposits are valued for their water absorbing properties (Pawluk, 1995), but the landscape positions on which they occur obviously have a considerable flood hazard. This is not unlike floodplain agriculture in many parts of the world where floodplain soils are the most fertile on the landscape, but floods themselves can be devastating to crop production.

The value of sand in Zuni farming is exemplified in one particular interaction. During a discussion about a recent workshop on increasing soil organic matter one farmer summarized, "So, when you add all that compost and manure you can turn clay into sand, right?" In another interaction, this time with an Anglo dryland farmer from nearby Ramah, New Mexico, whom I visited with our Zuni collaborators, we all knelt in the middle of dryland alfalfa field to sift the fine red sand through our fingers. The farmer exclaimed, "This is the best soil you'll see anywhere!" (Personal communication, Richard White, Ramah, NM, 1995) – not an easy concept for a native of Iowa, but the Zunis agreed.

Questions about water control and runoff irrigation invariably lead to answers relating to the need to protect crops from floods and to protect fields from erosion rather than diverting or harvesting runoff. The farmers emphasize erosion control practices that maintain depositional regimes and dissipate flood energy, but their priorities have usually been interpreted as spreading water over crops as irrigation. When asked how they control runoff for crops farmers would take me far up slope from fields and show me brush check dams in arroyo channels.

When talking about erosion control the Zunis generally did not refer to specific

techniques and methods as much as alluding to general knowledge of the range of possibilities in the environment. Asked where they learn erosion control practices most said, "from our grandparents" or "from the old people," but one farmer said he just learned by doing. Pressed about whether he learned from parents or grandparents he said, "Dad was the same way, he taught us to learn by doing." This reflects a common theme in my interactions with Zuni farmers: a combination of transgenerational knowledge and ability to innovate to deal with new and ever changing situations. One of our collaborating farmers put it very clearly in a statement about our entire scientific approach: "You scientists keep trying to figure out our system. We don't have any system because everything changes every year!"

Farmers make a clear link between uplands, runoff processes, and soil fertility. One elderly farmer interviewed by Pawluk (Pawluk, 1995) put it this way,

> There's a mountain over there; big flood comes in all the fields. All kinds of fertilizers and water...flood all these places here. ***Then make a good soil.*** There on top, those trees bring...what we call he:yalowe. These hills are a lot of he:yalo. So that's why they got the rich place, a little ways out from the wash, it's a soil; it's different (emphasis added).

On the other hand, many discuss the need to protect fields, describing negative impacts of flooding. One of Zuni's most respected elderly farmers, interviewed by Ferguson (1985) discussed severe erosion in Galestina Wash, stating, "It's really deep now ... It wasn't this deep I know ... And it's cut that much now in the last maybe 30 years...You take care of it probably won't cut as bad as will if you just leave it going, let it cut itself every year if it rains. See, rain what causes it" (Ferguson, 1985:117). The same farmer, interviewed by Ford (1985), detailed how posts and brush could be used to cause arroyos to fill with soil and disappear (Ford, 1985:40). One of the farmers I

interviewed described how, without continued work by himself and other farmers in Mullen Wash, this important farming area would be incised and much less valuable. He described their efforts in cutting brush and piling it in the arroyo far upstream from the alluvial agricultural area and stated strongly, in concurrence with the farmer interviewed by Ferguson, that nearby Galestina Wash was severely incised because this work was neglected.

The three randomly selected farmers I interviewed who discussed erosion control all reacted in the same way when asked whether they had erosion problems in their rainfed fields, essentially, "No, whenever we clear brush or prune trees we throw it all in the arroyos and it stops the erosion." Many of our informants discussed pruning the lower branches from pinyon (*Pinus edulis*) and juniper (*Juniperus* spp.) trees to improve sight distance for herders and increase forage production around the trees. This practice can be observed in many areas of the Zuni Reservation. Asked why he doesn't just cut the trees one farmer replied that they reduce wind. All the informants who discussed erosion control described similar methods to the farmer in the previous paragraph, piling brush and soil to slow floodwaters and filter sediments. One farmer explained that if he was clearing fields or pastures of brush and trees he completely fills arroyos with the material, but if he was just using what brush he needed to control downcutting he would spend more time layering the brush in well-placed structures. Construction and effectiveness of traditional brush erosion control methods is reported in chapter five.

All the farmers reacted negatively to mention of efforts by the tribe to control erosion, both by BIA crews and by the Zuni Conservation Project (ZCP). BIA methods include using heavy equipment to build earthen dams or install gabions or stone rip rap.

ZCP crews, funded by the Zuni Land Conservation Act (Hart, 1995), use hand labor to construct rip rap, flagstone grade controls, and log and stone check dams. All of the farmers that discussed erosion control explained that their own methods, using material available on-site, especially brush, work just as well or better, require much less labor, are much easier to maintain or replace when they fail, do not require multiple loads of rocks that tear up equipment and create haul roads and more erosion, and have an added benefit of improving grass production by clearing brush. All three of the randomly selected farmers that discussed erosion control felt very strongly about these issues and each described how he had tried to show both BIA and ZCP employees their traditional methods but were ignored. Two of these farmers said they had turned down ZCP offers to treat arroyos on their areas because the crews cause more erosion than they repair.

Gellis et al. (1995) evaluated different types of erosion control on the Zuni Reservation. They found that most large earthen structures had failed while most brush structures installed in an arroyo system by the Youth Conservation Corps in the 1970's remained intact and were fulfilling their intended functions. They concluded that both methods would perform better with periodic maintenance. Clearly the brush structures would be much easier to maintain than the large earthen dams.

Preference for soils on dynamic landscape positions means that continued productivity depends on preventing incision. Concentrated flows are damaging to current crops and they cut fields off from occasional renewal by fresh flood deposits. The value of flood deposits for productivity is definitely recognized by farmers, but as a long-term soil building material, not an immediate source of nutrients for crops. Our Zuni collaborators repeatedly emphasized that mixed alluvial deposits were good after a year

or two, but more detrimental than beneficial to crops in the field at the time of deposition.

When asked what factor determined whether a crop would be successful, farmers all said rain was most important, but not runoff. Two of the farmers described in detail the importance of fall and winter moisture in determining whether the next year's crop would produce. One described how you have to know the soil in each field and pay attention to how green the grasses and weeds are. Many also emphasized the importance of light rains or even cloudy, humid weather during the growing season.

Reports from earlier visits to Zuni also describe erosion control efforts by farmers. Stewart (1940) described the same type of brush and earth dams discussed by the Ferguson interviewee and shown to me by several farmers. His interpretation is that,

> the Zuni cultivator finds it easier to deflect the flood water out of the stream bed with a series of small brush-and-earth dams. ... The channel (elevation) itself is kept up close to the field so that this system of flood-water irrigation constitutes a wonderfully effective method of gully control (Stewart, 1940:337).

Stewart's interpretation is typical of how outside observers have defined these activities; erosion control as a side-effect of "water spreading." Stewart continues,

> The more thoughtful Zuni recognize the value of these methods in preserving the land. On a visit to Zuni during the past summer the Governor of Zuni remarked to the writer: 'Zuni farming always keeps the land good.' Trouble at times may be experienced from excessively strong flow of water, washing out hills of corn, or too much sand may be deposited onto portions of a field, but spectacular gullying at least is prevented.

Earlier work by Cushing, an ethnographer of the Zuni in the 1870's (Cushing, 1920; Green, 1979), describes initiation and first planting of new rainfed fields. Many authors interpret Cushing's work to support their own descriptions of "runoff" farming (Damp and Kendrick, 2000; Kintigh, 1985; Sandor, 1995), particularly this passage:

> The effect of the network of barriers is what the Indian prayed for – attributes, furthermore, as much to his prayer as to his labors – namely, that with every shower,

> although the stream go dry three hours afterward, water has been carried to every portion of the field, has deposited a fine loam over it all and moistened from one end to the other, the substratum. Not only this but also, all rainfall on the actual space is retained and absorbed within the system of minor embankments (Green, 1979:255).

On its own, this paragraph appears to describe a runoff irrigation system. However, in paragraphs before and after this passage, Cushing makes it clear that this comes at least one year before any crops are planted. He describes how the farmer has spent at least two springs "lifting the soil" (clearing vegetation and building sand berms) to reach this point, at which he prays, "bidding the mesas shake down streamlets. The streamlets shall yield torrents; the torrents, foam-capped, soil-laden, shall boil toward the shrine he is making, drop hither and thither the soil they are bearing, leap over his barricades unburdened and stronger..." (Green, 1979:255). No crops were in the field during the prayed for and received floods, but after such a flood, "the field is again left for a year, that it may become thoroughly enriched" (Green, 1979:255). He goes on to describe how soils of older fields are renewed by building brush windbreaks to capture wind-blown soil which is then redeposited by ephemeral stream flows.

Agronomically, Cushing's description suggests that Zuni farmers manipulate soil building processes to optimize moisture and fertility in newly cultivated fields. First, clearing the soil two to three years prior to planting would store moisture by eliminating plant uptake, much like modern crop-fallow dryland farming systems, so that when finally planted the soil profile would likely be full of stored rainfall. Second, thoroughly "lifting the sand" and building berms would create a rough surface to slow and spread the prayed-for torrents, encouraging infiltration and deposition but preventing evaporation from the soil through capillary rise; another concept of modern crop-fallow systems. Waiting at least a year after such a flood so that the soil becomes "thoroughly enriched"

is consistent with statements by our informants that flood deposits are beneficial a year or more after deposition. It is also consistent with composting practices, where fresh, high C-to-N ratio organic matter, such as that carried from Zuni's mesa top pinyon-juniper woodlands, is allowed to decompose at least one year so that microbial immobilization gives way to mineralization and increasing nutrient availability (Brady and Weil, 1996). The Zuni also use many cropping practices that conserve and optimize limited moisture and fertility, including seed selection, deep planting, widely spaced "hills" or clumps of corn, and the "three sisters" approach where corn, beans, and squash are planted together in the same field (Collins, 1914; Mangelsdorf and Reeves, 1939; Muenchrath, 1995).

Taken as a whole, Cushing's description seems to define a soil-building process practiced by Zuni farmers for non-irrigated farming, rather than the common definition of "runoff irrigation." The time frame of this description, from initial clearing to first planting, is at least three seasons but somewhat open-ended, suggesting that the farmer may wait as long as necessary for a flood of sufficient magnitude to deposit sediments.

Zuni Hydrology: Is "Runoff Irrigation" Possible?

Review of rainfall and hydrological data support the notion presented by interviewees that non-irrigated farming relies more on soil properties able to optimize frequent minor rain events than on diversion of runoff as "irrigation." The analyses suggest that "runoff irrigation," where crop production relies on supplemental moisture from ephemeral stream flow, is not feasible at Zuni. Long-term annual and growing season precipitation (Western Regional Climate Center, 2000a) show great variability (Figure 1–1) suggesting that averages, and agricultural models or assumptions based on them are of limited utility to understanding Zuni farming.

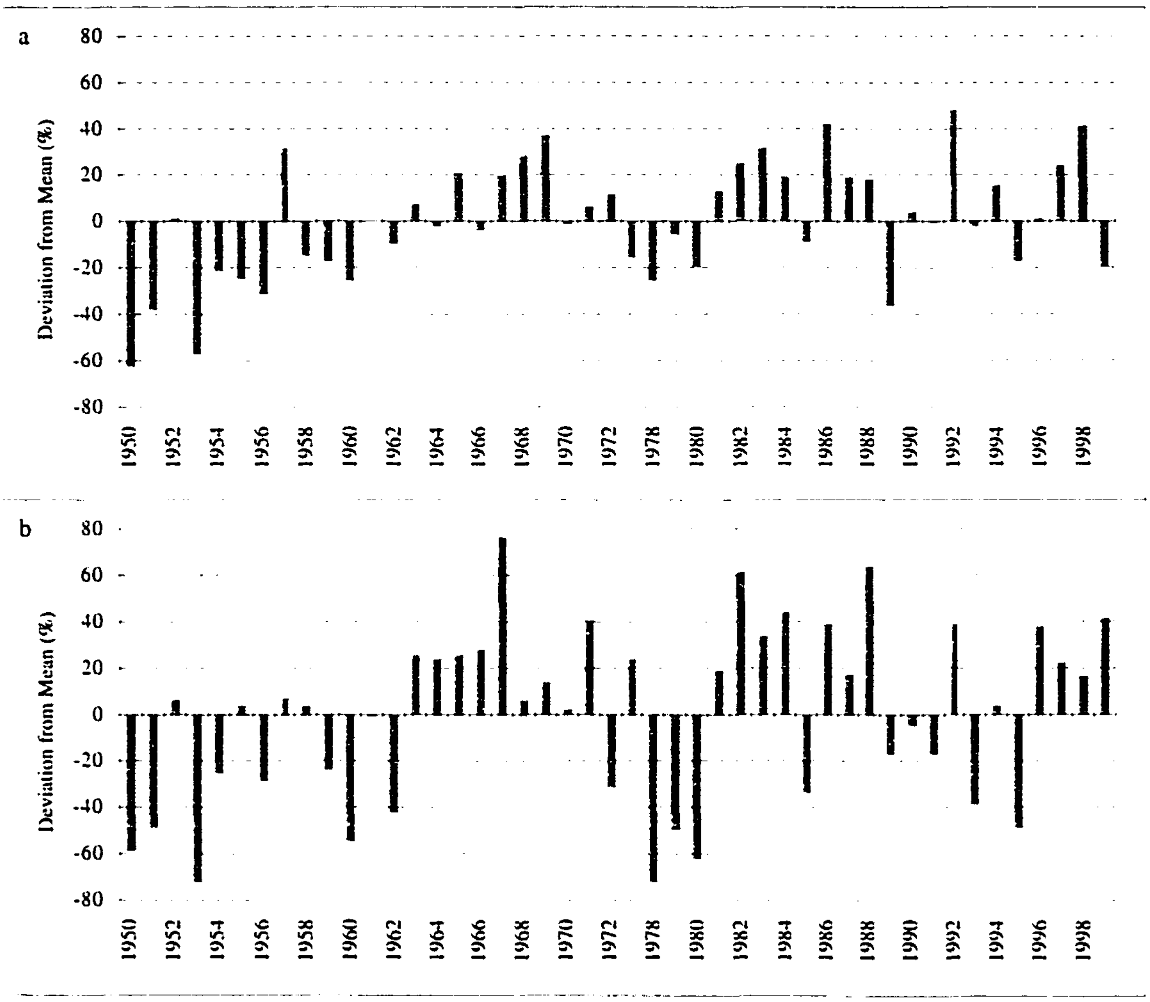

Figure 1–1. Annual (a) and growing season (b) deviation from mean precipitation, Zuni, New Mexico. Data for 1973-1977 are missing. Based on Western Regional Climate Center, 2000b.

Though highly variable, rainfall follows a distinct seasonal pattern (Figure 1–2). The "monsoon" months of July, August, and September account for an average of 44 percent, and as much as 80 percent, of the 315 mm average annual precipitation. Spring months of April, May, and June account for only an average of 12 percent of annual precipitation and as little as two percent while fall/winter months (October to March) account for 44 percent with a wide range from 4 to 74 percent.

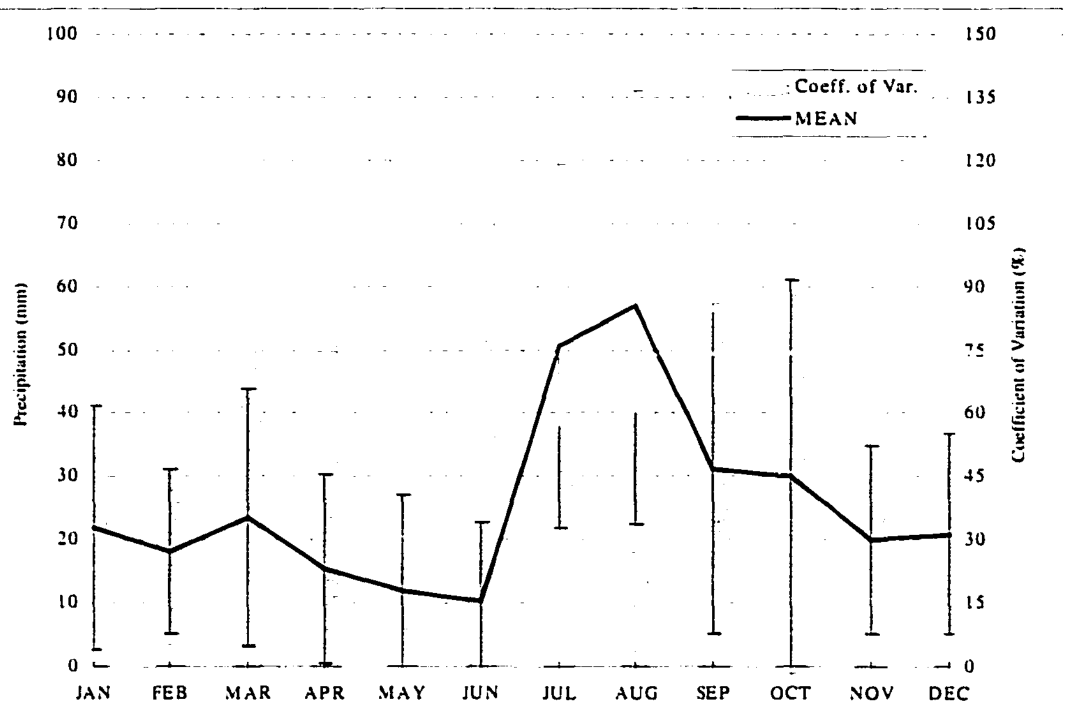

Figure 1–2. Long-term average monthly precipitation and coefficient of variation, 1949-1999 (Western Regional Climate Center, 2000a). Error bars represent precipitation standard deviation.

The coefficient of variation (CV) (standard deviation divided by the mean) is a measure of predictability. Based on the 46 years reported, annual precipitation can be expected to vary by 26 percent from the mean in any given year; from 230 to 400 mm per year can be considered normal. CV's for monthly and seasonal variation are much greater, ranging up to 126 percent in May. Precipitation is most dependable during the late summer, but CV's are still 57, 60, and 84 percent in July, August, and September, respectively. Spring CV is 70 percent, summer 40 percent, and fall/winter 38 percent over the 45 years of record (Western Regional Climate Center, 2000a).

Analysis of long-term daily precipitation shows that a large majority of rainfall comes as "minor" events while rain intense enough to generate runoff is rare. Balling

and Wells (1990) analyzed over 85 years of daily precipitation records from Zuni to investigate long- and short-term climate change effects on landscape processes. They group the long-term data by intensity (Balling and Wells, 1990:611), showing an average 63 precipitation days per year over the 1897-1985 period: 56 days with less than 12.7 mm, 5 days with 12.7 to 25.4 mm, and less than 1 day yr^{-1} with over 25.4 mm. Multiplying the midpoints from these groups (using 25.4 to 31.8 mm for the upper category) by the number of days and correcting to the 1897-1985 average of 336 mm yr^{-1} shows that a large majority of annual rainfall comes as minor events of less than 12.7 mm per day (Figure 1–3).

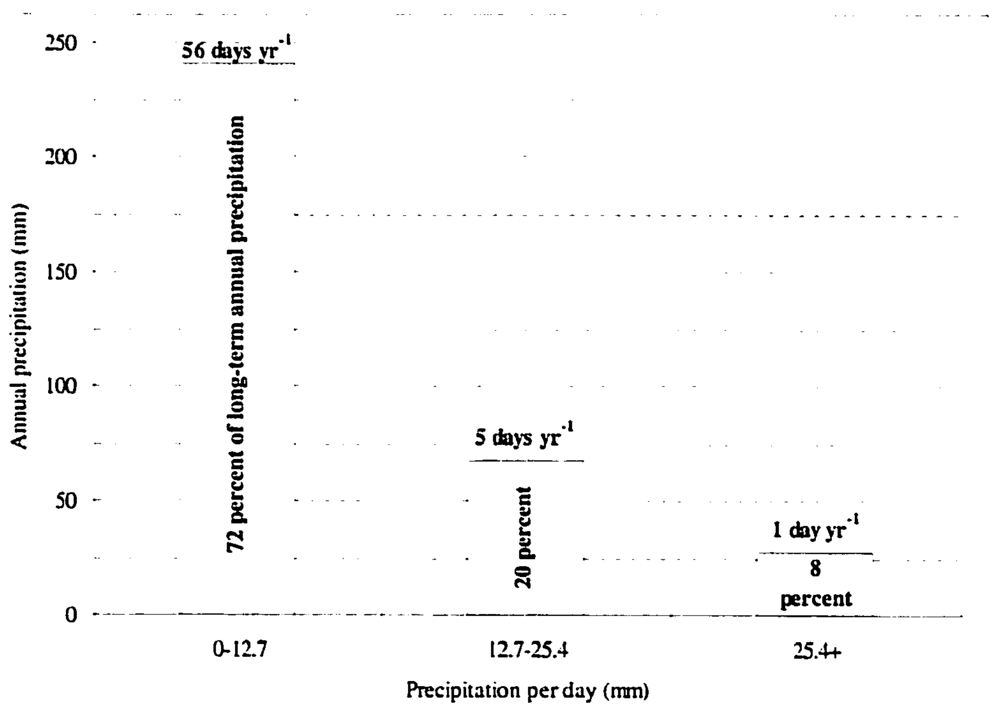

Figure 1–3. Frequency and intensity of daily rainfall at Zuni (Balling and Wells, 1990).

Relatively minor events with less than 25.4 mm d^{-1} usually do not generate ephemeral stream flow but, given favorable hydrologic properties of the sandy surface

soils, are probably important for crop production.

Frequency and magnitude of runoff suggest that arroyo flow occurs in the five study watersheds less than once per year on average, far too infrequently to be considered reliable irrigation. Table 1–2 reports estimated peak discharge from 2 through 100 year recurrence interval flow events and the recurrence interval of channel flow initiation extrapolated from the 2 to 25 year discharge estimates (Figure 1–4).

Table 1–2. Calculated peak discharges for selected recurrence intervals and recurrence intervals of runoff thresholds (when watershed storage is overcome and channel flow begins) for selected watersheds.

				Recurrence Interval (yrs)					
Watershed	Area	Evaporation*	Runoff threshold**	2	5	10	25	50	100
	(ha)	*(mm)*	*(yrs)*	*Peak Discharge*** (m^3/s)*					
Paquin	179	1280	1.22	0.6	3.0	5.9	10.1	14.1	15.7
Weekoty	124	1280	1.26	0.5	2.4	4.9	8.3	11.6	12.7
Sanchez	67	1280	1.33	0.3	1.7	3.6	6.1	8.3	8.9
Lalio	36	1280	1.40	0.2	1.2	2.6	4.4	6.0	6.2
Laate	8	1280	1.54	0.1	0.5	1.2	2.0	2.6	2.5

* Evaporation measured near Zuni (Thomas et al., 1997:170; station 09387050).

** x-axis intercept calculated from regression analyses of 2 through 25 year discharge ($r^2=1$; see Figure 1-4).

*** USGS Region 11 regression equations: $Q = b(A)^c$ for 2 and 5 year recurrence intervals and $Q = b(A)^c(E)^2$ for 10 to 100 year where A is watershed area in square miles and E is pan evaporation in inches, and b and c are constants (Thomas et al., 1997:56).

Peak flows based on USGS regressions (Thomas et al., 1997) show that, on average, flow is initiated in the five watersheds less than once a year. The runoff threshold concurs with Balling and Wells' (1990) >25.4 mm rainfall threshold (1.2 yr recurrence interval), ranging from 1.2 years in the Paquin watershed to 1.5 in the Laate watershed. The average period of record for stations in Region 11 is 20 years, so calculations for the less frequent, higher magnitude events are less reliable (Thomas et al., 1997).

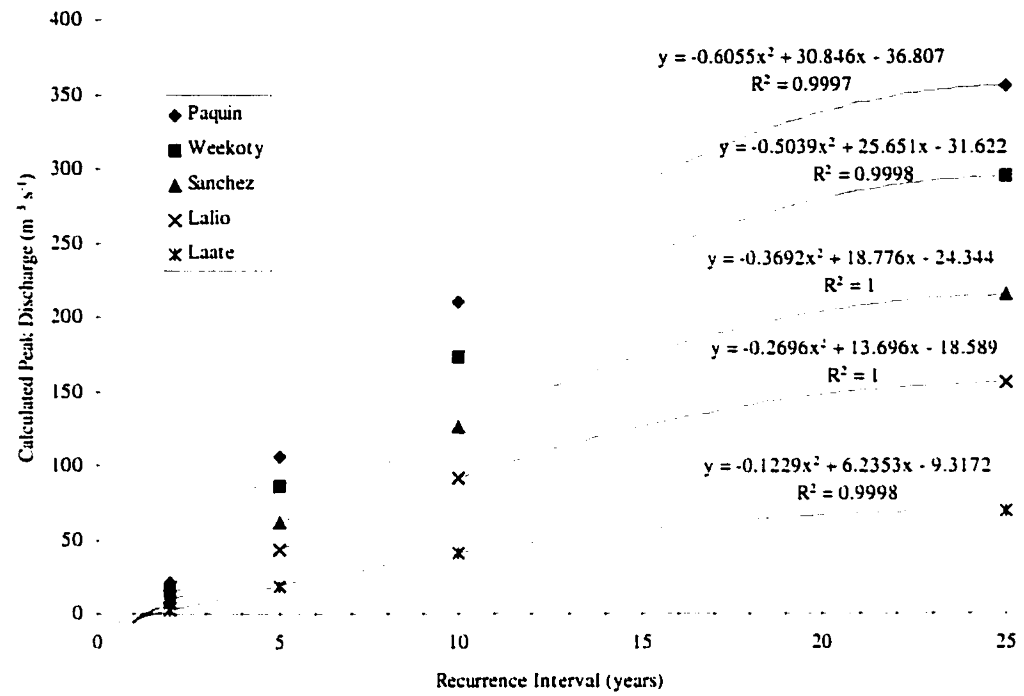

Figure 1–4. Regression analyses on calculated peak discharges for 2 to 25 year events for each of five study watersheds. Extrapolation to the x-axis gives estimated recurrence interval of runoff threshold where watershed storage is exceeded and flow begins (see Table 1-2).

Some watersheds used in Thomas et al's. (1997) regression are smaller than the five watersheds studied here, but most were larger.

Water yield estimates from a distributed model (McDougal et al., 1985) also suggest that runoff may be less frequent than would be required for reliable irrigation. Yields from rainfall events reported in Table 1–3 (based on the Natural Resource Conservation Service curve number method) also suggest that the runoff threshold is exceeded on an average frequency of about once per year, except for the Laate watershed where minimal transmission losses lead to minor yields with light precipitation.

Table 1–3. Runoff yield for selected rainfall amounts (24 hour period) (Balling and Wells, 1990; Western Regional Climate Center, 2000b) and watersheds by Natural Resource Conservation Service curve number method (McDougal et al., 1985) minus transmission losses (Lane, 1990).

		Precipitation (mm)*							
		12.7	25.4	30.5	40.6	45.7	55.9	63.5	71.1
		Recurrence Interval (yrs)**							
Watershed	Area	0.4	1.2	2	5	10	25	50	100
	Area (ha)	Yield (m^3)							
Paquin	179	0	4200	7067	13919	17764	26062	32693	39592
Weekoty	124	0	2337	4269	9132	11951	18168	23231	28560
Sanchez	67	0	1037	2008	4502	5964	9214	11877	14693
Lalio	36	0	1149	1862	3539	4471	6468	8054	9698
Laate	8	2	114	228	545	738	1178	1545	1939

* 12.7 and 25.4 mm amounts are categories used by Balling and Wells (1990); others are from precipitation recurrence interval maps for New Mexico (Western Regional Climate Center, 2000b).

** 0.4 and 1.2 are calculated from regression analysis of 2 through 25 year precipitation amounts.

Farming as Soil Conservation: Does Zuni Rain Fed Farming Prevent Erosion?

If activities intended to protect soil desirable for rainfed agriculture effectively prevent arroyo cutting, as is the view of farmers interviewed by myself and others (Ferguson, 1985; Ford, 1985; Stewart, 1940), extensive farming of the past, when Zuni subsistence depended on it, may have significantly impacted erosion rates. This section explores parallels in Zuni socio-economic, demographic, and environmental history as circumstantial evidence that social change away from agriculture contributed to accelerated arroyo erosion.

S. G. Wells and others correlate short-term climatic perturbation with channel incision to create a convincing case for early 20th century initiation of currently incised arroyos (Balling and Wells, 1990; Lagasse et al., 1990; Wells, 1987). Balling and Wells (1990) show that severe drought from 1898 to 1905 was followed by three years of especially wet weather. They postulate that the prolonged drought depleted vegetation

and contributed to severe erosion during the following wet years. Many authors show relationships between climatic perturbations and drastic erosion (Bull, 1997; Cooke and Reeves, 1976; Elliot et al., 1999) but Wells and his colleagues represent an extreme of climatic determinism, stating strongly that arroyo cutting is completely unaffected by human activities (Balling and Wells, 1990; Wells, 1987). While others have shown impacts of intensified land use, this chapter puts forth the notion that *removal* of farming activity contributed to accelerated downcutting at Zuni.

The juxtaposition of dry and wet years after 1900 corresponds with major socio-economic shifts away from agriculture that left fewer Zuni farmers to fight the ensuing erosion. Rhode (1990) estimates a per capita requirement of about 1.2 ha of corn for Zuni subsistence, which was exclusively grown by rainfed methods. Zuni population at the time of contact with Europeans in 1540 is estimated at between 4000 and 6000 (Ferguson, 1996), or about 5000 to 7000 ha of corn in production. The population plummeted to under 1500 shortly after contact, fluctuating around this level until the mid-1900's. Establishment of American forts in New Mexico and Arizona after 1846 created a market for Zuni corn and a rise in production. In 1853 Captain L. Sitgreaves reported that nearly 5000 ha of corn were planted by the Zuni (Ferguson, 1985). According to McCall and Frazer (1968), army quartermasters from Fort Wingate expressed frustration at Zuni leaders' refusal to sell corn unless they had at least a full year supply in storage.

The U.S. Army's demand for corn may mark the beginning of a cash economy at Zuni. As Anglo-American settlers took over the market after 1870 (Ferguson and Hart, 1985) the need for cash was probably well established and, along with a burgeoning

demand for Native American crafts (Dilworth, 1992), led many Zuni to focus on silversmithing and other crafts rather than agriculture (Vogt and Albert, 1966). Other forms of employment, such as hourly work in Gallup and forest fire fighting, eventually drew many Zunis away from farming as well (Bohrer, 1960; Leighton and Adair, 1966).

Zuni was wracked with severe epidemics during the 19th century, the worst of which, small pox during 1852-53, 1876, and 1897-1899, each took 25 to 50 percent of the population (Ferguson, 1985). The impact of these devastating periods on Zuni society is not documented, other than decreases in population, but must have been severe and undoubtedly impeded farmers' ability and desire to maintain rainfed fields. With each epidemic an infrastructure of dependency upon U.S. Government aid increased. The last smallpox epidemic corresponds with the beginning of the severe seven year drought reported by Balling and Wells (1990).

This period also corresponds with major land reform efforts by the U.S. Government on Indian Reservations, many of which proved ecologically inappropriate and culturally devastating (Beatty Davis, 1997; Cleveland et al., 1995; Hurt, 1987; Wessel, 1987; White, 1983). On the Zuni Reservation these efforts included irrigation development and grazing policies that designated lands for either agriculture or livestock (Ferguson, 1985). Construction of large irrigation reservoirs created irrigable lands where each Zuni family was allotted a parcel. Rainfed farming outside these designated agricultural areas became difficult because fencing requirements and imposed land tenure did away with the traditional system where any Zuni could gain use rights by developing and using a piece of land (Cushing, 1920; Green, 1979). A historical low in rainfed farming due to combined effects of epidemic, drought, and the increasing cash economy

may have facilitated this shift toward irrigated farming and livestock by weakening resistance to allotment. Farming continued to be an important activity for the majority of Zuni families well into the 20th century, however, especially in drainages surrounding Zuni Pueblo. Figure 1–5 shows how alluvial zones in nearly every ephemeral stream channel around Zuni Pueblo were occupied by farm fields in 1937.

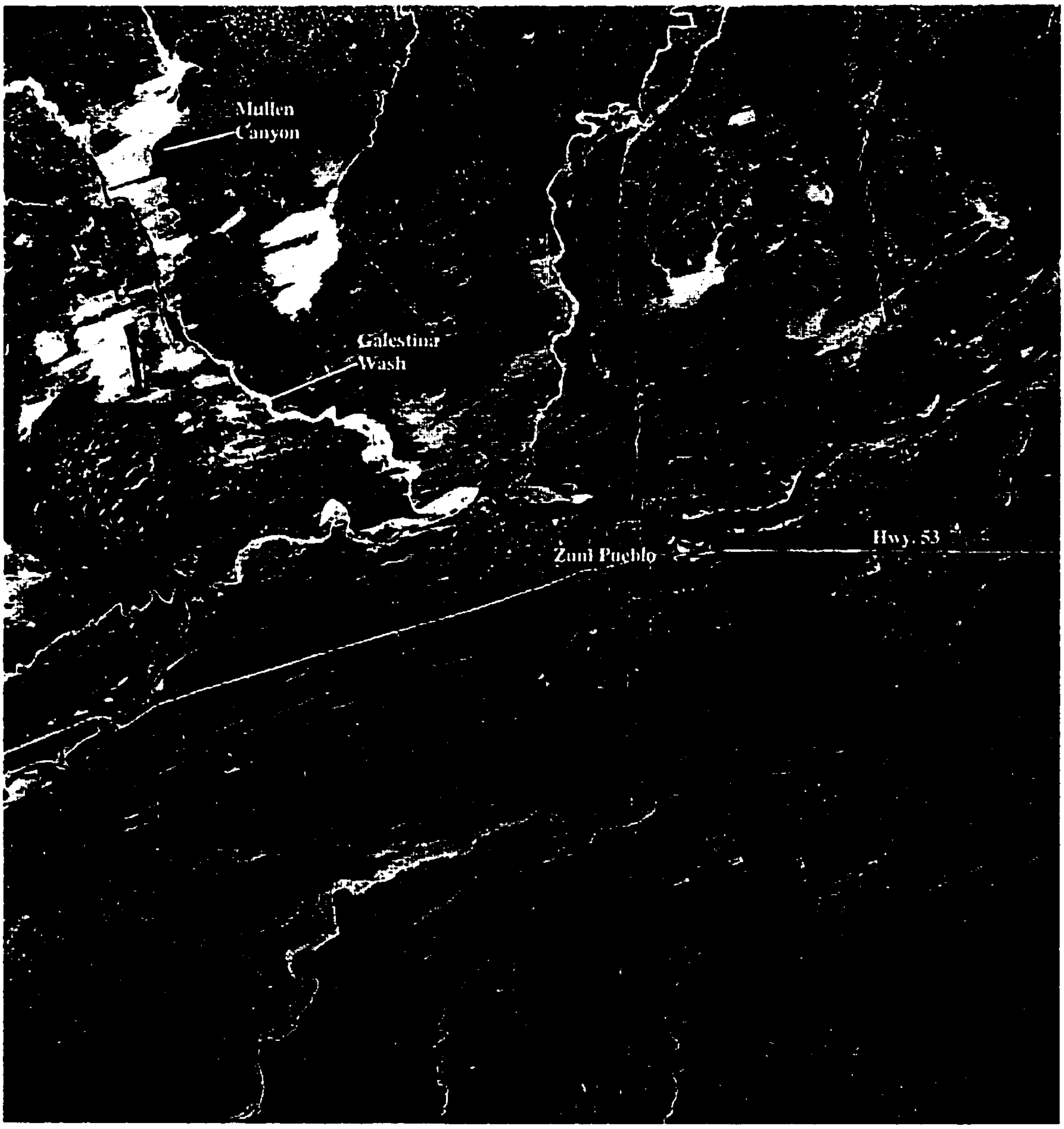

Figure 1–5. Areal photograph of Zuni Pueblo, May 1, 1937. Lighting conditions highlight ephemeral stream courses and alluvial agricultural zones.

The combined effect of economic shifts, devastating epidemics, land reform policies, and, ultimately, prolonged drought, would mean that the number of Zunis actively practicing ancient methods of mitigating flood force and facilitating overbank flows was likely at an all-time low precisely when erosive floods described by Balling and Wells (1990) occurred. While climatic perturbation is likely responsible for triggering the downcutting episode, several decades of neglect of rainfed alluvial fan corn fields that had been maintained out of pure necessity for centuries, may have contributed to more severe erosion than would have occurred in the past. In other words, while ephemeral channels clearly go through natural cycles of degradation and aggradation (Schumm et al., 1984), Zuni survival has depended on interventions that maintained depositional regimes. Decades of decline in dispersed rainfed agriculture activities for myriad social and cultural reasons, as well as an all time low in Zuni attention to the landscape, may well have contributed to the severity of downcutting early in the 20th century.

CONCLUSIONS

Zuni farmers describe a rainfed farming system very different from that envisioned by scientists studying historic and prehistoric non-irrigated farming techniques. Farmers focus on soils with hydrologic properties that make the most of relatively dependable winter moisture and low intensity summer rains. These loamy and sandy soils often overlay finer layers and occur as flood deposits in active alluvial zones of discontinuous ephemeral streams. The farmers' descriptions suggest that crop production relies on duality in rainfall events: frequent low intensity rains supply relatively dependable moisture and less frequent floods (< 1flow yr^{-1}) provide deposits

with optimal soil properties. Farmers facilitate deposition of such soils and protect channels from downcutting with simple techniques utilizing brush, branches, and stones available in the immediate vicinity of erosion problems. Brush removal doubles as range improvement which, in many cases, is the primary objective of erosion control.

While non-irrigated farming of the Zuni and other Southwestern Native American groups has historically been described as runoff irrigation where crop production depends on ephemeral stream flow after thunderstorms, precipitation and hydrological data suggest that such flows occur far too infrequently to be considered irrigation. Low intensity rainfall events that do not generate stream flow are very frequent, however, and together with highly permeable alluvial soils and specialized cultivation techniques, may better explain corn production by native farmers.

Rainfed farming was responsible for a large part of Zuni subsistence until late in the 19th century when socio-economic changes, epidemics, and government land use policies combined to drastically reduce the number of Zunis growing rainfed corn. Farming declined over the last decades of the 19th century, shortly after which combined effects of drought followed by flood led to severe channel incision in many Zuni watersheds. The chronology of these events suggests that if such a drastic climatic perturbation had occurred in a previous century, when alluvial zones were invaluable to Zuni subsistence, the activities of farmers would likely have mitigated the severity of resulting channel incision. As such, Zuni dependence upon and manipulation of alluvial zones may have created fluvial systems that were the "subservient domain of the social system" until abandonment in the 20th century.

While alluvial deposits are not as directly valuable for food production as in

previous times, they still perform hydrological and ecological functions critical to Zuni economy and culture, such as livestock forage, wildlife habitat, flood mitigation, water storage, and protection of downstream water quality. These values extend beyond Zuni across the western U.S. and other semiarid regions. Zuni focus on small watersheds where stream power is manageable with simple and rapid techniques may represent a useful approach for watershed restoration.

Prior to U.S. government intervention, the Zuni apparently had developed a land use system geared toward optimal utilization of a variable and dynamic environment. Long-term cultural stability in such a dynamic and unstable landscape requires levels of flexibility and adaptive decision-making beyond those in most definitions of sustainable agriculture. As global climate becomes increasingly variable opportunities for production may become increasingly ephemeral and scattered. Further study of the traditional Zuni approach to rainfed farming may provide a template for management systems required under such conditions.

The following chapters report investigations of hillslope, fluvial, and alluvial fan components of the rain fed agroecosystem and traditional methods for preventing and restoring damage done by arroyo cutting.

Chapter 2: Soil biochemical implications of hillslope processes and rainfall patterns

INTRODUCTION

> I'll tell you now, this is my way back. There's a mountain over there; big flood comes in all the fields. All kinds of fertilizers and water...flood all these places here. Then make a good soil. There on top, those trees bring...what we call *he:yalowe*. These hills are a lot of *he:yalo*. So that's why they got the rich place, a little ways out from the wash, it's a soil; it's different.
>
> Zuni farmer, 1991 (Courtesy of Roman Pawluk)

Alluvial soils are the most productive part of semiarid landscapes (Bull, 1997), but connections to hillslope processes; recognized and utilized by generations of Zuni farmers (Pawluk, 1995), remain largely unexplored in scientific work. Hillslope processes control runoff, sediment, and organic matter dynamics that determine the nature of downslope fluvial systems (Abrahams, 1986; Fisher and Grimm, 1985; Leopold et al., 1966). Besides supporting over 2000 years of Zuni agriculture (Damp and Kendrick, 2000), soils of alluvial landforms at Zuni store runoff and sediments, mitigate destructive floods, and produce diverse, productive vegetation for livestock and wildlife (Bull, 1997; Lagasse et al., 1990). However, many flood plains and alluvial fans are threatened by channel entrenchment that circumvents contributions from hillslopes and eliminates hydrological and ecological function and value (Elliot et al., 1999). This chapter reports investigations of organic matter transformations and sediment movement through the upland hillslope component of headwater watersheds.

Hillslope erosion and sediment transport are well understood with respect to soil loss and water yield (Bull and Kirkby, 1997; Selby, 1993). To date most research has focused on quantity – sediment mass and water discharge – rather than composition.

Sediment budget studies in semiarid watersheds underscore the importance of hillslopes as the source of materials that ultimately shape fluvial systems. Leopold et al. (1966), in their classic study of sediment budgets of southwestern ephemeral streams, demonstrated that 98 percent of the sediment flowing from watersheds comes from hillslope sheet and rill erosion. This suggests that much sediment entering the fluvial system is biologically enriched O and A horizon material eroded from wooded slopes.

Concern with the nutrient content of sediments is increasing as degradation of uplands is linked to quality of downstream aquatic habitats (Cole et al., 1990; Slattery and Burt, 1997), but organic matter transformations through hillslope systems, and relationships between hillslope processes and alluvial soils, are poorly understood. Many studies document systematic changes in soil properties with slope position, and define processes associated with sediment movement, sorting, and accumulation pertaining to soil morphology (Honeycutt et al., 1990; Kleiss, 1970; Ruhe and Walker, 1968). Each of these studies documents increasing organic matter concentrations with distance from summit along trends that mirror fine soil fractions, but do not attempt process-oriented explanations of organic matter dynamics.

Aguilar and Heil (1988) noted increasing C, N and P concentrations, as well as narrowing C to N ratios, with decreasing elevation on North Dakota rangeland hillslopes. They suggest accumulation of runoff-transported organic matter on lower slopes and infer progressive downslope increases in inorganic N concentrations. In their studies of semiarid Colorado grasslands, Schimel et al. (1985) also found increasing organic matter concentrations with distance from summits, but they noted decreased mineral N with higher C to N ratios on lower slopes. They attribute this unexpected trend to greater

inputs of C from increased organic matter production due to enhanced soil moisture. Increased C causes microbial immobilization to out pace mineralization rates, leading to lower concentrations of mineral N.

Other studies of the effects of vegetation on soil organic matter content and composition show that different species can have distinct impacts (Klemmedson, 1991; Klemmedson and Wienhold, 1991). Klemmedson (1991), for instance, found that Gambel oak (*Quercus gambelii*) had significant positive impacts on soil fertility in Arizona ponderosa pine (*Pinus ponderosa*) stands; much more than actinomycete-associated N-fixing shrubs such as mountain mahogany (*Cercocarpus* spp.).

Most studies of soil organic matter distribution in semiarid Southwestern pinyon-juniper (*Pinus edulis-Juniperus* spp.) woodlands and scrub-shrub grasslands focus on tree and shrub encroachment that increases soil heterogeneity, creating vegetated patches with depleted interspaces (Allen, 1991; Schlesinger et al., 1996). Development of these "islands of fertility" are both cause and effect of changing runoff and erosion regimes in a positive feedback relationship (Abrahams et al., 1995). Recent work focuses on vegetation patch effects on runoff and erosion (Wilcox, 1994), redistribution of sediments among patches and inter-patches (Reid et al., 1999), and effects of shrub patch-induced accelerated erosion on nutrient losses (Schlesinger et al., 1999).

Rainfall characteristics are crucial driving variables in dryland hydrology and many studies define relationships between rainfall volume, intensity, duration, frequency, and other parameters, and production of runoff and sediment (Branson et al., 1981). However, few studies examine ecological roles of various types of rainfall events. Rainfall in the Southwest follows distinct seasonal patterns that may have striking

impacts on movement and transformation of organic matter. Wilcox (1994) showed that both soil infiltration rates and soil erodibility in pinyon-juniper woodlands also follow seasonal trends. Reid et al. (1999) identify differing effects on runoff and erosion of three types of rainfall events: 1) minor storms (<15mm) that are frequent but rarely produce runoff; 2) major, low intensity frontal storms that can produce a great deal of runoff with low sediment concentrations; and 3) convection thunderstorms with high intensity rainfall that produces a great deal of runoff and erosion. Sala and Lauenroth (1982) suggest that the high frequency, low-impact minor rainfall events drive growth of herbaceous vegetation as well as organic matter mineralization in shallow surface horizons of semiarid soils. Frequent wetting and drying cycles, coupled with minor downslope movement of organic matter and sediments mean that small rainfall events may partly decompose materials later transported by less frequent flushing-flow events.

Ironically, all the soils of the Zuni Indian Reservation, where farming precedes the birth of Christ, have been classified as economically unarable in the recently completed soil survey (Natural Resource Conservation Service, in press). Alluvial soils formed by interactions between watershed and climatic factors may be productive in spatially and temporally ephemeral patterns (Seastedt and Knapp, 1993) that are difficult to define with current agricultural models, but, nonetheless, supported the Zuni for many centuries. Conventional assessment procedures that fail to comprehend dynamic agroecological settings undermine rationality of traditional methods and may be partly responsible for cultural disruption and desertification in semiarid lands (Cleveland et al., 1995; Ellis and Swift, 1988; Fujisaka, 1997). As such, careful interdisciplinary analyses could improve understanding of native techniques while defining previously

misunderstood landscape positions that have important cultural, ecological, and hydrological functions.

MATERIALS AND METHODS

Site Description

I analyzed soil resource, landform, and vegetation distribution and runoff/erosion processes in three small watersheds above long-term runoff agricultural fields on the Zuni Indian Reservation, New Mexico (Figure 2–1).

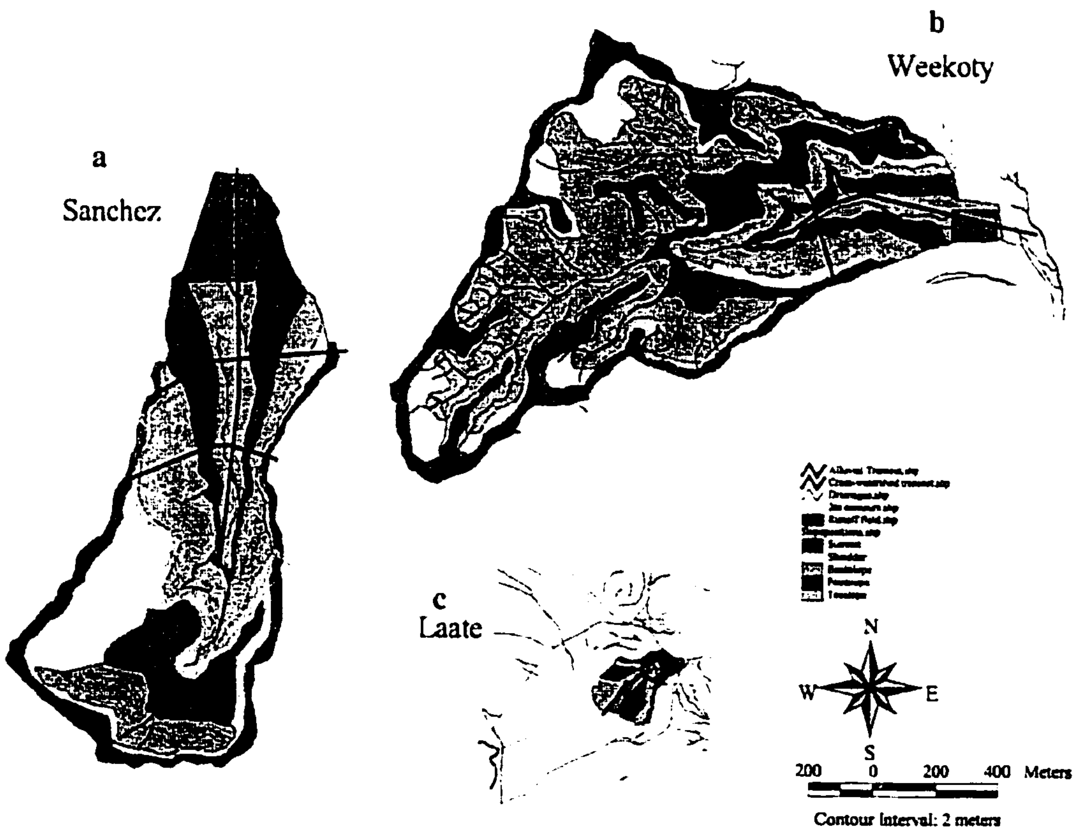

Figure 2–1. Watershed study sites with cross-watershed transects and slope position delineations.

The Sanchez watershed covers 68 ha about one km south of the small farming village of Pescado, near the eastern edge of the reservation, the Laate watershed covers about 8 ha one km northwest of the farming village of Lower Nutria, and the Weekoty watershed covers 125 ha between Pescado and Nutria. Each of the watersheds is characterized by steep walled canyons cut into sandstone and shale members of the Gallup Sandstone (Anderson et al., 1989). Hillslope profiles fit a modified version of Dalrymple's landsurface model (Gerrard, 1992) combined with the five slope positions defined by Ruhe and Walker (1968) (Figure 2–2). Layered shale and sandstone members underlie mesa top positions; thickly bedded sandstone creates fall faces, thick, weathered shale underlies transportational midslope and colluvial toeslope positions; and sandy or loamy alluvium forms toeslopes. The canyon-floor alluvium in each watershed is bisected by an arroyo ranging from 1 m depth at the Laate site to over 6 m at the Sanchez and Weekoty sites. In each case the channel ends above a runoff agricultural field.

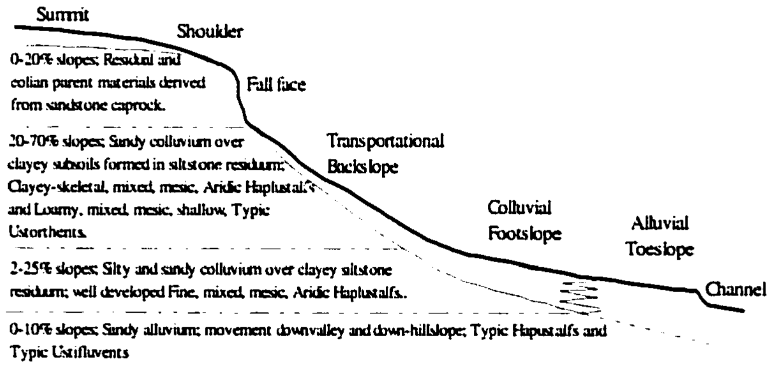

Figure 2–2. Composite hillslope: schematic profile common to each of the eight topolithosequences studied (based on Dalrymple in Gerrard, 1992).

Watershed Soil, Vegetation, and Landform Distribution

Two cross-watershed transects were established at the Sanchez watershed and one each at the Weekoty and Laate watersheds for a total of eight divide-to-drainage hillslope transects (Figure 2–1). Landform, cover, and soils were sampled at three points across the hillslope each 15m along the transects (on the base line and 5 m each direction perpendicular to it). At each sample point I noted landform type, classified and estimated soil cover (vegetation by species), and collected 0-15 cm depth soil samples. Plant cover, as well as litter, bare soil, gravel, cobble, stone, and boulder, were estimated using a square frame constructed from PVC tubing. Plot size varied to reflect canopy size (Grieg-Smith, 1983) with 0.25 m^2 for herbaceous plants and other soil cover parameters, 1 m^2 for shrubs, and 4 m^2 for trees. I estimated cover classes in the field and then converted to percentages (cover class midpoints) for analysis (Daubenmire, 1968). Soil samples consist of five to seven 0-15cm depth samples from within each 1m^2 plot mixed and subsampled to provide one sample per plot.

Runoff and Yield and Composition by Slope Position

To determine sediment and runoff water yield and composition from the most important slope positions I installed 16 sediment plots at the three sites (six mesa top sites, six backslope sites, and four footslope sites). Each trap captured runoff and sediment from a 20m^2 bounded plot 2.5 m wide by 8 m long (Gellis, 1998). I selected locations representative of each position and with similar vegetation cover of around 30 percent bare soil. Samples were captured in five gallon buckets from which one gallon thoroughly mixed subsamples were collected after each runoff event. Runoff volume

was calculated from the depth of runoff in the collection buckets which I recorded in the field. Subsamples were allowed to settle in refrigerators at 4°C and then decanted. Sediments were dried and weighed for calculation of sediment yield and stored for lab analysis. The supernatant was preserved with a dilute solution of phenylmercuric acetate and stored for solute analysis. During 1996 I collected samples from all 16 traps at the three study watersheds but this proved logistically unfeasible during the frequent (sometimes > 1/day) rain events in late summer. During 1997 and 1998 I sampled six newly established traps at the Weekoty site, where rainfall volume, duration, and intensity were recorded at a tipping bucket rain gauge equipped with a CRX-20 data logger (Campbell Scientific Equipment, Inc., Logan, UT). Precipitation in each plot was recorded at a rain gauge each time sediment and runoff samples were collected.

Runoff and Sediment Yield and Composition by Cover Type

To investigate the effect of vegetation cover on sediment and nutrient yield from hillslopes I installed two sediment traps in each of six cover types in the Weekoty site. The traps captured sediments and runoff from $1m^2$ bounded plots located on footslopes with 7 to 12 percent slopes. The traps were installed in spring of 1997 and monitored during 1997 and 1998. Sediments and runoff were measured and treated the same as for the $20m^2$ slope position plots.

Laboratory Analysis

Soil and sediment samples were air dried in the field and transported to labs for chemical and physical analyses. Table 2–1 summarizes the analyses completed in each watershed. Particle size distribution was determined using the sieve and pipette method

(Gee and Bauder, 1986), with samples pretreated with a 30 percent hydrogen peroxide reagent for organic matter digestion and a sodium hexametaphosphate solution for clay dispersion. Soil pH was measured electrometrically using a 1:1 suspension (weight basis) of soil in distilled water using a glass electrode (McLean, 1982). Total C and N concentrations were determined on subsamples ground to pass a 76μm sieve using a Fissions EA1100 dry combustion CNSHO analyzer (Fissions Inst., Inc., Milan, Italy). Inorganic C concentration was determined with a coulombmeter on a subset of samples and found to be insignificant relative to total C concentration, therefore, total C content was assumed to be identical to organic C content. Total phosphorus concentrations were determined by alkaline oxidation (Dick and Tabatabai, 1977). Available phosphorus concentrations were measured by the Olsen extraction method (Olsen and Sommers, 1982). Nitrate-N and ammonium-N concentrations were determined in KCl extracts with a Lachat flow-injection procedure (Lachat Instruments, Milwaukee, WI; Method 12-107-04-1-B). Runoff samples were analyzed for cation concentration by atomic absorption spectrophotometry and anion concentration with a Tecnicon AutoAnalyzer.

Table 2–1. Data sets analyzed for each of the eight study hillslopes.

	Hillslope							
	Weekoty		Laate		Sanchez 1		Sanchez 2	
Soil Property	S	N	S	N	E	W	E	W
Texture	x	x	x	x	x	x	x	x
pH	x	x			x	x	x	x
Organic C	x	x	x	x	x	x	x	x
Total N	x	x	x	x	x	x	x	x
Total P	x	x	x	x	x	x		
Available P	x	x	x	x	x			
Nitrate-N					x	x	x	x
Ammonium-N					x	x	x	x

Data Analysis

Slope, soil, and landform observations were analyzed as a summit to toeslope continuum and as map units based on slope positions described by Ruhe and Walker (1968) and Dalrymple (Gerrard, 1992). I generated point-scatter graphs for all cover and soil property data against distance from summit for each of the eight hillslopes and ran regression analyses using the trendline function in Microsoft Excel 5.0. I then ran similar regressions on composites of the data from all eight hillslopes together and on means calculated for each 10 units along the composite hillslope. For the composite analyses I plotted values against relative distance from summit (actual distance/total length). I also ran regressions on unweighted slope position means from each of the eight hillslopes to compensate for the variable number of sample points among the transects. Least significance differences were calculated for the composite means using the SPSS statistical package LSD function.

I analyzed runoff and sediment yield and composition both as concentrations averaged across all events in each slope position (mesa top, backslope, and footslope) or

cover type, and as average annual yield per slope position or cover type (plots were monitored from May to September each year of the study period). I calculated average annual yields for each slope position by generating plot-year sums of sediment and runoff (total from all events for each plot each year it was monitored) and then dividing by the number of plot-years (# yrs x # plots in each slope position). Yields of each constituent of sediment (sand, silt, clay, total C, total N, total P, and available P) were derived from sediment yields and constituent concentrations. I used the same procedure to calculate average annual yields for the vegetation cover plots (2 plots/cover type x 2 years = 4 plot-years per cover type). Only data from events where all the traps functioned properly are included in the analyses. One third of the samples (50 out of 154) were not used in the analyses because of malfunctions (typically scour caused part of the runoff to bypass or undercut the trap). In some cases collection buckets overflowed but it was assumed that the buckets acted as stilling basins so that most sediments settled in the bucket as water spilled out the top. Sediment mass from these instances were used directly but runoff volume was calculated based on rainfall-runoff relationships developed for each trap (resulting values are unweighted means).

Rainfall data from the tipping bucket rain gauge were used to calculate standard statistics for precipitation analysis based on a 15 minute gap to separate distinct rainfall events. Parameters calculated for each event and used for regression analyses against runoff and sediment properties include total precipitation, maximum intensity, duration of event, duration of maximum intensity, time from start of event until maximum intensity, and length of rainless period before start of event (Ferreira, 1990).

I integrated transect and runoff/sediment data using fine scale (1:5000; 50 cm

contour interval) watershed maps of each site (base maps created by Koogle & Pouls Engineering, Inc., Albuquerque, New Mexico), along with field traverses, to delineate each slope position throughout the watersheds. The area of each slope position was calculated using Arcview 3.0 (ESRI) and the aerial extent of each cover type within each slope position was calculated from the transect cover data. Then the cover and slope position runoff and erosion data were combined by creating cover factors as follows: 1) values from the grass plots were set to equal one (most similar to cover of slope position plots); 2) the value for each constituent analyzed was divided by the value for the grass plot; 3) resulting conversion factors were then multiplied by the average annual slope position yields to get corrected yields by cover type for each slope position; 4) these values were then multiplied by the total extent of each cover type-slope position set within each watershed to get total annual yields of each slope position. Average net soil redistribution (loss and storage) during the study period was calculated from these corrected yields for one hillslope. Similar techniques based on transect data have been used to calculate landscape scale distribution of soil organic C and nutrients (Yonker et al., 1988) and to estimate net soil redistribution from soil loss modeling results (Lindstrom et al., 2000).

RESULTS

Hillslope Transects

Data from the hillslope transects are presented and analyzed both as a composite summit-to-toeslope continuum (averaged every 10 relative distance units from summits) and as means by slope position. Hillslope continuums allow analyses of progressive

changes along the hillslopes while means by slope position allow extrapolation as values associated with map units. The hillslope continuum data show the same trends as the slope position designations. Regressions run on weighted means for each watershed yielded similar results to the composite data, so only plots of unweighted composite hillslope continuum data are presented.

Slope and Soil Morphology

Hillslope morphology on the Zuni Indian Reservation, as in much of the Colorado Plateau, is largely a function of horizontal layers of Cretaceous sandstones and shales. At our study sites indurated, cliff-forming sandstones act as caprocks over more erodible, slope-forming shales, shaping hillslope profiles much like that defined by Dalrymple (Gerrard, 1992) (Figure 2–2). Summit positions are generally broad, nearly level mesa tops with shallow Entisols formed in sandstone residuum or sandy eolian materials. Shoulder positions are often dominated by bare, scoured sandstone with pockets of shallow, sandy eolian material. Backslopes typically have A horizons formed in sandy colluvium over siltstone residuum. This sequence of dynamic, mobile surface materials over stable, clayey subsoils follows a continuum from shallow A-2Cr horizon sequences on upper backslopes, gradually thickening with accumulation of slope wash material, and probably with increased moisture, to deep, well developed A-Bt-2Btss-2Cr Alfisols on footslopes. Toeslope soils form in a mixture of materials deposited from the local hillslope system and alluvial materials deposited by the valley fluvial system. The valley floors of our study sites are bisected by deep arroyos so that the landforms I designated as toeslopes act as both relatively inert alluvial terraces in the fluvial system and active depositional toeslopes in the hillslope system. This transition in functional landform is

reflected in well developed Bt horizons that indicate long-term stability of the fluvial terrace, overlain by fresh-appearing loamy sediments (lacking structure and significant organic matter incorporation) deposited from adjacent hillslopes.

Vegetation Distribution

Vegetation patterns in the three study watersheds are marked by distinct patchiness typical of pinyon-juniper woodlands and scrub-shrub grassland communities, and by nearly mutually exclusive ground cover vegetation and tree canopy (Figure 2–3).

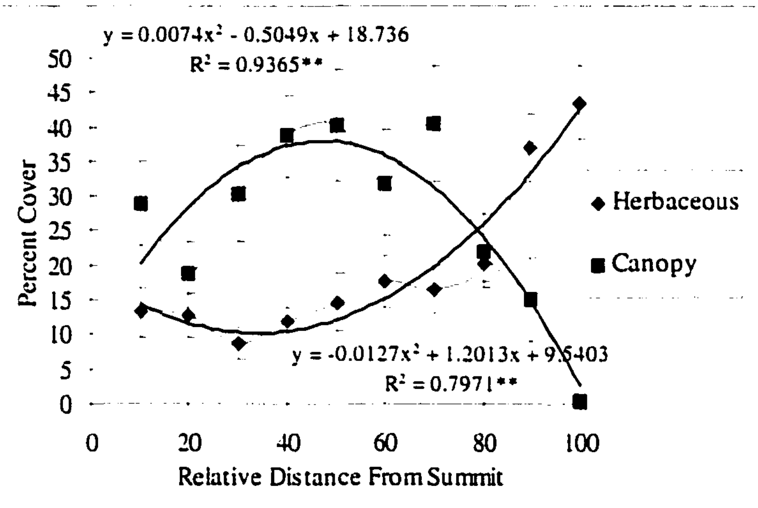

Figure 2–3. Tree canopy and herbaceous cover along composite hillslope continuum presented as average values of 10 unit increments (error bars represent standard error for each 10 unit increment. Backslope positions are ~27 to 55 and alluvial toeslopes are ~89-100 on the X axis. *,**: significant at 0.05 and 0.005 level, respectively.

The patchiness creates high variability in cover plot data (standard deviations are generally higher than means) but the large sample size represented by all eight hillslopes considered together yields highly significant trends: backslopes range up to 60 percent tree cover with only 10 to 15 percent herbaceous ground cover vegetation. Toeslopes show the opposite pattern with herbaceous vegetation covering up to 90 percent and tree canopy dropping to zero. Cover by forest litter mirrors tree canopy cover with the

highest occurrence on backslopes. Summit and shoulder positions generally have lower overall tree cover (larger interspaces) and more herbaceous cover than backslopes. Microbiotic soil crusts are most common on summit positions and cover a large proportion of the summit at the Weekoty transects. Shrubs, except for big sagebrush (*Artemisia tridentata*), do not follow a distinct trend, but are most abundant on summit and footslope positions (Table 2–2).

Table 2–2. Estimated percent areal cover averaged across all sites by slope position. Data from all eight hillslopes. Values followed by different letters are significantly different (LSD test).

Slope Position	n	Grasses	Forbs	Shrubs	Total Trees	Oaks	Juniper	Pinyon	Big sage-brush	Pond-erosa pine	Litter	Bare Soil	Microbiotic crusts
		%											
Summit	35	9ab	8a	17a	30ab	11ab	8ab	5ab	0a	5a	32ab	35a	2.9a
Shoulder	37	5ab	6a	10a	19a	3ac	3bc	14a	2a	0b	22a	27a	0.4ab
Backslope	136	6ab	5a	18a	38b	17b	9a	11a	0a	2b	36b	26a	0.3b
Footslope	69	12b	16b	11a	21a	1c	10a	9ab	8b	0b	27ab	30a	2.0ab
Toeslope	47	20c	19b	36a	2c	0c	0c	2b	24c	0b	20a	33a	1.1ab

Species are divided into distinct associations by slope position (Table 2–2). Backslopes are characterized by pinyon, juniper, and Gambel oak (classified as a tree) growing singly or in clumps with thick litter layers beneath their canopies and bare soil between. Summit and shoulder positions typically have the largest component of ponderosa pine along with pinyon and juniper, as well as Douglas-fir (*Pseudotsuga mensiezii*) in protected areas. Tree stands are more open on summits than backslopes and the wider interspaces are often covered by grass, typically *Stipa* spp., blue grama, bottlebrush squirrel tail (*Sitanion hystrix*), and mutton grass (*Poa fendelaria*), shrubs, typically wavy-leaf oak (*Quercus undulata*), mountain mahogany (*Cercocarpus montanus*), flowering ash (*Fraxinus cuspidata*), and antelope bitterbrush (*Purshia*

tridentata), and microbiotic crusts. Toeslopes are covered by big sagebrush, western wheatgrass (*Agropyron smithii*), and blue grama with components of rabbitbrush (*Chrysothamus nauseosus*) and weedy herbaceous vegetation in wash areas.

Soils associated with clumps of oak, pinyon, juniper, and forest litter have concentrations of organic C and nutrients much higher than bare soil and over twice the overall average concentrations for all plots (Table 2–3). Patches dominated by grass, forbs, big sagebrush, and microbiotic crusts are not statistically different from bare soils with respect to organic C concentrations. Soils under oaks have the highest concentrations of organic C, total N, and over five times more nitrate-N and twice as much ammonium-N and available P than the overall average concentrations.

Table 2–3. Effects of dominant cover type on soil characteristics. Criteria represents the highest well represented dominance of each cover type as sampled along the hillslope transects. Values within columns followed by different letters are significantly different at the 0.05 level (LSD test).

Cover	Criteria	*n*	pH	Organic C	Total N	Total P	C:N	Available P	NO_3-N	NH_4-N
	%			$g \cdot Kg^{-1}$				$mg \cdot Kg^{-1}$		
Grass	>40	19	6.5ab	14.1ad	1.12a	0.36a	13ac	7.7a	1.1ac	0.85a
Forbs	>40	15	6.6ab	15.4acd	1.21a	0.22b	13ac	7.5a	1.9ac	1.10a
Oaks	>50	23	6.5ab	26.6b	1.65bc	0.28ab	17b	10.7a	9.2b	1.71a
Juniper	>50	15	6.7ab	21.9bc	1.39ab	0.33ac	16ab	8.0a	3.6abc	0.70a
Pinyon	>50	18	6.8a	20.5ab	1.81c	0.28ab	13ac	8.6a	2.3ac	0.60a
Big sagebrush	>40	18	6.5ab	14.9acd	1.29ab	0.23b	11c	9.6a	2.7ac	0.97a
Litter	>75	50	6.3b	24.9b	1.55bcd	0.26bc	17b	8.5a	5.5ab	0.98a
Bare soil	>75	27	6.5ab	10.5d	1.22a	0.26bc	9d	3.3a	1.3c	1.19a
Microbiotic crusts	>25	7	6.4ab	6.1acd	1.11ad	0.24ab	13abc	3.5a	1.3abc	0.74a

Surface Soil Physical and Chemical Properties

Surface (0-15cm depth) particle-size distribution follows distinct trends that reflect lithology and soil horizon development. Summit and shoulder positions, underlain by the sandstone caprocks, have significantly higher sand contents than other positions (Table 2–4). Textures of backslope and footslope soils reflect their siltstone substrate with the lowest sand contents and highest silt and clay contents, though

Table 2–4. Concentrations and ratios of soil properties averaged by slope position for all three study sites. Values followed by different letters are significantly different at the $P = 0.05$ level as determined by LSD procedure in SPSS statistical package.

Slope Position	Mean Slope	Sand[1]		Silt[1]		Clay[1]		pH[2]		Organic C[1]		Total N[1]		Total P[3]	
	%	%	*n*	%	*n*	%	*n*		*n*	*mg kg⁻¹*	*n*	*mg kg⁻¹*	*n*	*mg kg⁻¹*	*n*
Summit	7	62 a	*34*	20 a	*35*	18 a	*35*	6.2 a	*26*	11.2 a	*33*	1.1 a	*34*	0.28 a	*23*
Shoulder	14	66 a	*36*	21 a	*37*	13 b	*37*	6.5 ab	*28*	14.2 ab	*34*	1.0 a	*35*	0.27 a	*33*
Backslope	33	44 b	*131*	30 b	*130*	26 c	*131*	6.6 b	*116*	19.2 c	*121*	1.4 b	*122*	0.30 a	*86*
Footslope	12	49 bc	*69*	27 bc	*69*	24 c	*69*	6.7 c	*63*	14.7 b	*69*	1.2 a	*69*	0.32 a	*57*
Toeslope	5	54 c	*47*	26 c	*47*	20 a	*47*	6.7 bc	*44*	12.2 ab	*47*	1.2 a	*47*	0.20 b	*30*

Slope Position	Available P[4]		Nitrate-N[5]		Ammonium -N[5]		C:N		C:P		Available P/ Total P		Ammonium-N/ Total N	
	mg kg⁻¹	*n*	*mg kg⁻¹*	*n*	*mg kg⁻¹*	*n*		*n*		*n*		*n*		*n*
Summit	2.7 a	*23*	1.7 ab	*11*	0.51 a	*11*	12 ad	*32*	49 a	*21*	0.012 a	*22*	0.0004 a	*10*
Shoulder	5.0 b	*27*	2.4 ab	*9*	0.82 ab	*10*	14 bc	*34*	64 ab	*30*	0.022 b	*27*	0.0006 ab	*8*
Backslope	5.6 b	*74*	2.1 a	*79*	0.78 b	*79*	15 c	*118*	77 b	*78*	0.023 b	*74*	0.0005 a	*72*
Footslope	5.4 b	*35*	1.1 b	*45*	0.73 ab	*46*	13 ab	*69*	55 a	*57*	0.022 b	*35*	0.0006 b	*46*
Toeslope	7.3 c	*18*	1.4 ab	*36*	0.83 b	*36*	10 d	*47*	67 ab	*30*	0.038 c	*18*	0.0007 b	*36*

1: data from all eight hillslopes; 2: no data from Laate site; 3: no data from Sanchez 2 hillslopes; 4: No data from Sanchez 1 West or Sanchez 2 hillslopes; 5: data from Sanchez watershed only.

slopewash results in coarser texture than the underlying residuum. Toeslope soil texture is intermediate between summit/shoulder soils and backslope/footslope soils, possibly a reflection of combined fluvial and hillslope depositional processes; the fluvial system may contribute sandier deposits and the hillslope system finer materials. Plotted as a continuum from proximal summit positions to distal toeslopes (Figure 2–4), the transect soil particle size data follow significant parabolic trends which are opposite to expected trends for hillslopes with only one parent material source (Brubaker et al., 1994; Ruhe and Walker, 1968). The trend in the fine soil fraction closely follows that of tree canopy and associated litter cover, while the sand fraction parallels cover by shallow-rooted herbaceous vegetation.

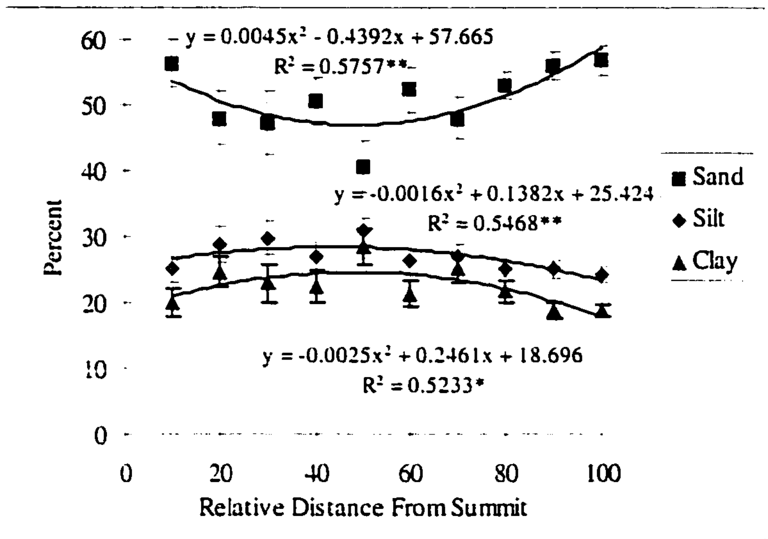

Figure 2–4. Soil texture along composite hillslope continuum. *,**: significant at 0.05 and 0.005 level, respectively (see Figure 2-3 for additional explanation).

Soil chemical properties also follow significant, both as a continuum and as a comparison of mean values by slope position. Soil pH increases from 6.2 at summit positions to 6.7 at footslopes along a linear trend, and then drops slightly at the toeslope (Table 2–4). Total C, N, and P each follow highly significant negative parabolic trends (Figure 2–5) with lowest values at summit and toeslope positions and highest at backslopes, opposite theoretical trends for soils with constant parent materials. C:N ratios follow a similar negative parabolic trend suggesting fresh organic matter inputs on the forested backslopes. These trends parallel those of the fine soil fraction; organic matter constituents are known to adhere to clay particles and clay-derived aggregates. In this case, however, highest C:N ratios on backslopes (corresponding to the finest soils and densest forest cover) suggest C, N, and P contents are attributable to fresh forest litter rather than sorption to silt and clay particles. Soil phosphorus can be derived from recycling of organic matter or weathering of parent materials. In this case, similarities between C, N, and total P suggest phosphorus associated with organic matter.

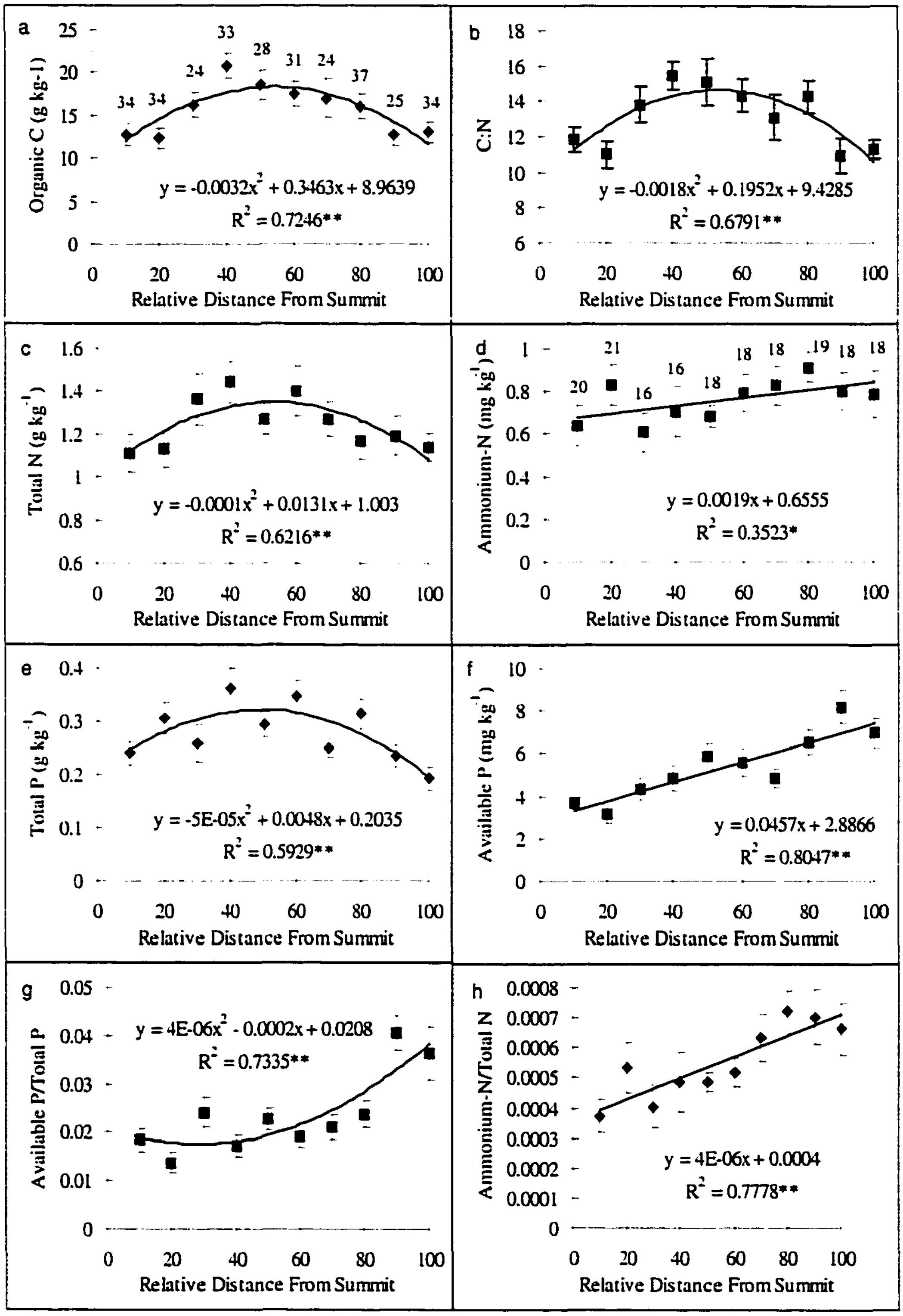

Figure 2–5. Organic matter and nutrient concentrations and ratios versus relative distance from interfluve (meters at point/total hillslope length x 100). Each point represents mean of 10 composite hillslope units. Error bars represent standard error. *,**: significant at 0.05 and 0.005 level, respectively.

error. *,**: significant at 0.05 and 0.005 level, respectively.

Plant-available P concentrations increase along a highly significant linear trend from summit to toeslope positions (Figure 2–5). Ammonium-N, however, appears to increase linearly through the backslope and footslope sections. Nitrate-N content is highly variable and does not follow a distinct trend along the hillslopes. Both available P as a proportion of total P and ammonium-N as a proportion of total N follow highly significant increasing trends from summit to toeslope positions.

Runoff and Sediment Yield

Total summer precipitation was below average in both 1997 and 1998 (Table 2–5), but varied a great deal month by month.

Table 2–5. 1997 and 1998 summer precipitation at the Weekoty study site.

	Long-term average (mm)	**1997 (mm)**	1997 percent of average	**1998* (mm)**	1998 percent of average
May	11.7	**20**	*171*	**0.8**	*7*
June	8.9	**33.7**	*379*	**0.1**	*1*
July	52.6	**25.6**	*49*	**69.8**	*133*
August	59.7	**43.8**	*73*	**8.9**	*15*
Total:	132.9	**123.1**	*93*	**79.6**	*60*

* 1998 data collected only through August 19.

A total of 154 samples were collected from 38 storms at the 20m^2 plots during the three year study and included 104 samples from 28 storms in the analyses. Runoff for the three seasons was highly variable among the plots so that there were no significant differences among means by slope positions (Table 2–6). Percent runoff (mm runoff/mm precipitation* 100) averaged 3.8 for all the plots-years combined and ranged from 1.4 to 8.1 percent. This compares favorably to nine hydrologic studies in pinyon-juniper environments reviewed by Wilcox (1994.

Table 2–6. Mean annual runoff and erosion yields by slope position, 1996-1998, based on averages of sums from each plot for each field season. Yields represent minimum annual yields from each slope position; at least one runoff event per year was missed at each trap. Numbers within each column are significantly different (P = 0.05) from those followed by different letters (LSD test).

Landform	n	Runoff	Sediment	Sand	Silt	Clay	Total C	Total N	Total P	Av. P	C:N	C:P	Av. P/TP
		$l \cdot m^{-2}$	$g \cdot m^{-2}$				$mg \cdot m^{-2}$						
Sum/Shldr	8	1.9 a	44 a	27 a	6 a	5 a	894 a	49.6 a	12.4 a	0.44 a	15 a	95 a	0.04 a
Backslope	8	2.8 a	125 b	61 a	33 b	27 b	2154 b	116.2 b	34.2 b	0.77 a	15 a	53 b	0.02 b
Footslope	6	2.3 a	57 a	31 a	16 a	9 a	1202 ab	73.9 ab	18.7 a	0.55 a	12 a	64 b	0.03 b

Average annual erosion rates show highly significant differences among the slope positions (Table 2–6). Sediment yields of 44 to 125 g m^{-2} yr^{-1} measured at the erosion plots are much greater than those measured by Gellis (1998) in the nearby Nutria watershed (6.0 to 11.7 g m^{-2} yr^{-1}) but compare favorably to erosion rates of 380 to 760 g m^{-2} yr^{-1} estimated by Natural Resource Conservation Service using the USLE for the Nutria area, considering that no extremely heavy precipitation events occurred during our three year study period and data was collected only during summer. Part of these discrepancies are likely due to year to year annual precipitation that varies greatly in the Zuni region.

A total of 230 samples were collected from the 1m^2 plots during 1997 and 1998 and included 156 in the analyses. Runoff yields from the 1 m^2 plots (Table 2–7) were also highly variable with no significant differences among the cover types. The bare soil and grass plots yielded nearly identical amounts of runoff, but the bare soil plots yielded over 4.5 times more sediment than the grass plots.

Table 2–7. Mean annual yields by soil cover type. Yields are based on averages of sums of from each plot for each field season. Yields represent minimum annual yields from each covertype; at least one runoff event per year was missed at each trap. Numbers within each column are significantly different ($P = 0.05$) from those followed by different letters (LSD test).

Cover	n	Runoff	Sed	sand	silt	clay	Total C	Total N	Total P	Av. P	C:N	C:P	Av.P/TP
		$l \cdot m^{-2}$	$g \cdot m^{-2}$				$mg \cdot m^{-2}$						
Bare Soil	4	9.4a	486b	402a	54a	30a	7870ab	412ab	62.7B	2.33a	18a	92ac	0.04a
Crust	4	8.1a	441bc	346a	65a	31a	5028a	338ab	54.4bc	1.33a	14b	51a	0.03a
Oak	4	12.4a	402ab	251a	104a	47a	32572b	1527b	45.5ab	7.69a	20a	217b	0.07a
Juniper	4	8.3a	168ab	122a	30a	16a	4192a	209a	17.0ac	1.74a	20a	178bc	0.04a
Pinyon	4	8.9a	153ac	97a	30a	25a	3699a	194a	9.5A	1.32a	17ab	123ab	0.05a
Grass	4	9.4a	107a	72a	24a	11a	3296a	181a	15.0ac	1.23a	17ab	108ac	0.07a

Average annual erosion rates varied significantly among the $1 m^2$ plots (Table 2–7). Sediment yield is divided into two groups with bare soil (486g m^{-2} yr^{-1}) and microbiotic crust cover (441g m^{-2} yr^{-1}) yielding significantly more sediment and than pinyon (153g m^{-2} yr^{-1})and grass (107g m^{-2} yr^{-1}) plots. Oak and juniper plots yielded intermediate amounts of sediment (402g m^{-2} yr^{-1} and 168g m^{-2} yr^{-1} respectively).

Yields of sediment and runoff were considerably higher from the 1 m^2 cover plots than from the 20 m^2 slope position plots for the same rain events. This discrepancy is probably largely due to a scale effect: during the frequent minor runoff events longer slope lengths in the larger plots store sediment and runoff water (sediment and runoff moved within the 20 m^2 plots but not into the traps). The smaller plots were more sensitive to minor runoff events; the slightest movement of sediment and runoff within the plots was transported to the traps.

Runoff and Sediment Composition

Slope position, cover type, total sediment yield, and date of runoff events all had significant impacts on sediment physical and chemical properties. Concentrations of

dissolved mineral N and P in runoff were low and variable, however, and do not represent significant movement of nutrients in solution.

Sediment Texture

Slope position had the most significant effect on particle size distribution of sediments eroded from our plots (Table 2–8). Texture of sediments from the slope position plots is nearly identical to that of soils along the hillslope transects with the siltstone-derived backslope soils yielding the finest textured sediments and the sandstone-derived summit/shoulder soils the coarsest.

Table 2–8. Slope position effects on runoff and sediment yield and sediment composition. Values are averages of all samples from $20m^2$ plots during the three year study. Values within columns followed by different letters are significantly different at the 0.05 level (LSD test).

Land Form	n	Run-off	Sedi-ment	Sand	Silt	Clay	Total C	total N	Total P	Av. P	C:N	C:P	AvP/TP
		mm	*g m⁻²*		*%*			*g kg⁻¹*		*mg kg⁻¹*			
Sum/Shldr	34	1.9 a	45 a	66 a	21 a	13 a	31.4 a	1.88 a	0.328 a	11.6 a	17 ab	119 a	0.054 a
Backslope	39	2.8 a	125 b	45 b	30 b	25 b	23.4 b	1.37 b	0.336 a	9.8 a	18 a	74 b	0.029 b
Footslope	31	2.3 a	57 a	58 a	27 ab	16 ab	23.3 b	1.51 ab	0.310 a	10.4 a	16 b	79 b	0.037 b

Soil cover had less impact on sediment texture, but bare soil, microbiotic crust, and juniper plots yielded significantly sandier sediments than oak plots (Table 2–9). Sediments from all the $1m^2$ cover plots, located on footslopes, are sandier than those of footslope $20m^2$ plots, possibly a result of the scale effect discussed previously.

Table 2–9. Soil cover effects on yield and composition of sediment. Values are averages of all samples from 1m² plots during the two year study. Values within columns followed by different letters are significantly different at the 0.05 level (LSD test).

Cover	Sed. Yield	Sand	Silt	Clay	Organic C	Total N	Total P	Av. P	C:N	C:P	Av.P/TP
	$g\ m^{-2}$	%			$g \cdot Kg^{-1}$			$mg\ kg^{-1}$			
Bare soil	486	82a	12a	6a	24.4ab	1.35ab	0.281ab	12.4ab	17a	87ab	0.04ab
Crust	441	78ab	15ab	7a	12.9b	0.91b	0.246a	7.1b	14b	52b	0.03b
Oak	402	63c	26c	12b	82.0c	3.98c	0.355b	25.2c	20c	231c	0.07ab
Juniper	168	76abd	15ab	9ab	54.4d	2.77d	0.272ab	25.8c	19cd	200ad	0.10ab
Pinyon	153	61cd	22abc	17c	43.8ad	2.46d	0.320ab	20.1ac	18ad	137cd	0.06ab
Grass	107	67bc	23bc	10ab	38.5ad	2.17ad	0.334ab	17.7ac	18ad	115ad	0.05a

Sediment Organic Matter Characteristics

Concentration of organic matter and nutrients were highly variable among runoff events, but show significant impacts of both slope position and cover type over the three year study. While texture of sediments from the slope position plots were similar to those of the underlying soil, organic C concentration in sediment is nearly twice that of soils and sediment N concentration is about 1.5 times that of soils (Table 2–8). In contrast to the distribution of soil organic matter (which peaks at backslopes), sediment organic C and total N concentrations were highest from summit/shoulder positions. C:N ratios in sediment were considerably higher than in soils at all slope positions. Conversely, available P/total P is higher in sediments than soils at all three positions and highest in summit/shoulder sediments but lowest in soil from those positions. Available P is over four times more abundant in summit/shoulder sediments than soils and nearly twice so in backslope and footslope sediments than soils.

Soil cover type is also significantly correlated to organic matter and nutrient contents in sediments (Table 2–9). Concentrations of both organic C and total N in sediments from the oak plots are significantly higher than all the other cover types. Microbiotic crust plots yielded sediments with lowest concentrations of C, N, and P and

C:N ratios significantly lower than all the other cover types, possibly a result of the crust sequestering soil C and P as they fix N.

Watershed Scale Slope Position-Soil Cover Interactions

Table 2–10 shows estimated total annual loss from each slope position map unit in the three watersheds. These values are calculated from cover data from the transects multiplied by runoff and sediment yield corrected for cover effects and by the aerial extent of each slope position (see Figure 2–1).

Table 2–10. Estimated total annual runoff and loss of sediment and nutrients by slope position for the three study sites on total area basis.

Landform	Area	Run-off	Sed-ment	Sand	Silt	Clay	Total C	Total N	Total P	Av. P
	ha	*m³*	—*metric tons*—				—*kg*—			*G*
All Watersheds										
Sum/Shldr	71	1350	106	79.1	14.5	12.3	1658	83	18	632
Backslope	75	2245	442	211.3	126.5	104.0	7508	354	58	1843
Footslope	36	814	68	45.8	12.9	8.8	757	44	15	304
Laate										
Sum/Shldr	2	37	4	3.1	0.4	0.3	33	2	1	13
Backslope	1	29	6	1.6	0.5	0.5	30	2	1	10
Footslope	2	43	4	2.9	0.7	0.5	39	2	1	15
Sanchez										
Sum/Shldr	23	446	46	34.8	5.8	4.9	621	31	8	227
Backslope	18	514	107	61.1	23.9	21.5	1229	60	17	323
Footslope	17	388	39	26.4	7.6	5.2	407	23	8	153
Weekoty										
Sum/Shldr	46	867	57	41.2	8.3	7.1	1004	50	10	392
Backslope	56	1703	333	148.6	102.1	82.0	6250	293	41	1510
Footslope	17	383	24	16.5	4.6	3.1	311	18	6	136

These values show that extension of transect and runoff plot data to whole watersheds amplifies effects of backslopes in all except the Laate site where backslopes make up a smaller portion of the watershed. In the Sanchez watershed the summit/shoulder position is large because of a large area of bare exposed bedrock on the

mesa top that was classified as shoulder. Relative loss from adjacent hillslope positions, without appreciable movement of sediments through the fluvial system, suggests redistribution of materials during the frequent minor rainfall events during our study period. Figure 2–6 shows estimated redistribution sediments on the southern hillslope of the Weekoty watershed.

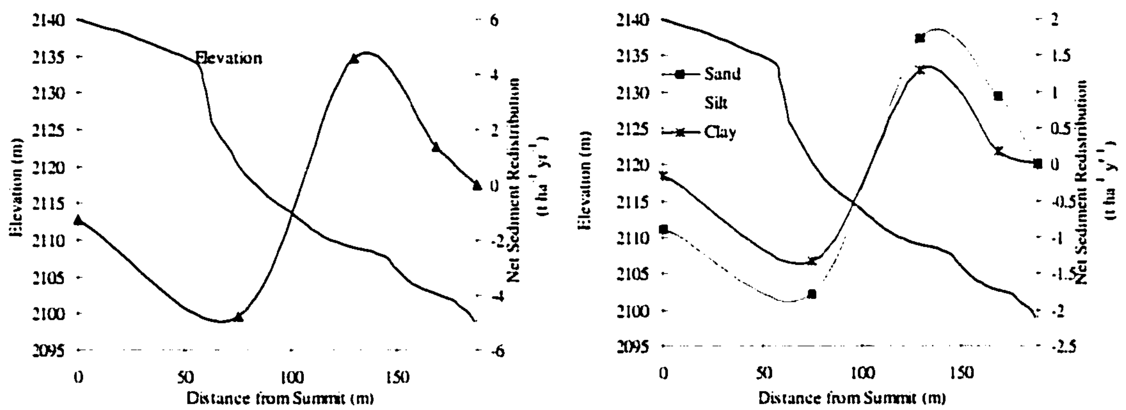

Figure 2–6. Annual net redistribution of soils on Weekoty South hillslope for study period. Indicates accumulation on lower slope position in absence of large, flushing flow events during the study period (based on sediment trap results and arroyo flow observations).

DISCUSSION

The horizontal stratigraphy of the Colorado Plateau, combined with the harsh, high elevation semiarid climate punctuated by intense convective summer thunderstorms, results in distinctive mesa-canyon topography with broad, level hilltops and steep, lithologically segmented hillslopes. Our data indicate that this unique combination of lithology, topography, and rainfall pattern drive slope and organic matter processes that in turn may affect soil productivity on alluvial landforms. Infrequent intense storms are responsible for shaping the landscape, but frequent minor events may play pivotal roles in processing forest floor organic matter, sustaining plant growth, and creating

accumulation of materials on lower slopes that may set the stage for major movement of materials during larger events.

Rainfall

Minor rainfall events that generate little or no runoff were far more frequent than larger events that generate ephemeral stream flows. The minor, low intensity events are generated on the fringes of convection thunderstorms or as more widespread frontal systems. Both of these types of storms are common in the summer at Zuni (Tuan et al., 1973). Reid et al. (1999) noted a similar dichotomy of rainfall events in a study at Los Alamos National Laboratory. Long-term daily precipitation data from Zuni shows that most precipitation comes as minor, non-runoff generating events (Figure 2–7).

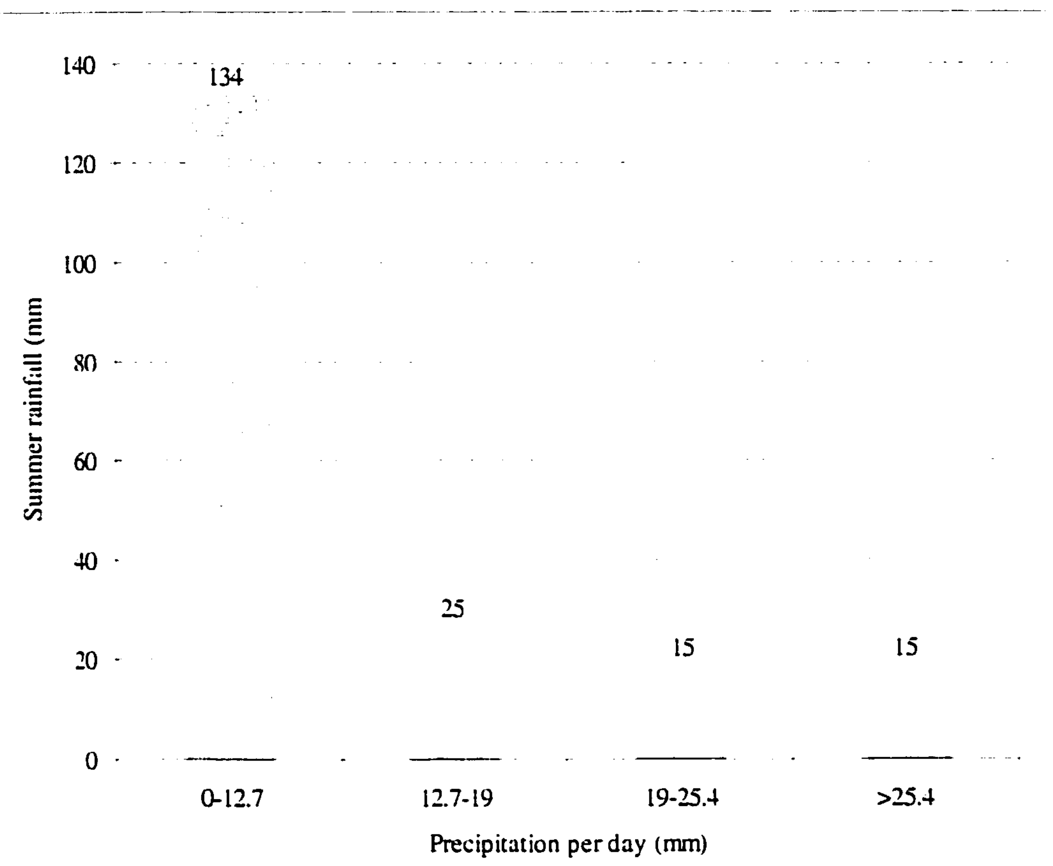

Figure 2–7. Distribution of summer (April-September) precipitation by amount day^{-1}, 1896-1985, Zuni Pueblo. Total average summer rainfall is 195 mm (SD = 54 mm). Indicates that 69 percent of summer rainfall comes as minor events of less than 12.7 mm day^{-1} and over 89 percent comes as minor events of less than 25.4 mm day^{-1} (based on Balling and Wells, 1990).

Data from our tipping bucket raingauge shows a strong negative correlation between rainfall intensity and rainfall duration, possibly a result of the two different types of storms. The intense, convection thunderstorms are responsible for significantly redistributing soil, sediment, and organic matter. However, rains that generate continuous flow through small watersheds occur with an average return frequency of 1.5 years or more. Our results show that many minor events generate runoff on hillslopes but few cause ephemeral stream flow. In 1997, for instance, rainfall was recorded on 52 days during the field season, collected runoff and sediment samples from hillslope plots

13 times, and noted minor, non-bedload transporting stream flow events three times. Runoff yield models run by Lagasse et al. (1990) for different scale watersheds on the Zuni reservation show similar results with upland drainages generating runoff 68 times more frequently than larger watersheds for the 2-year rainfall event and five times more frequently for the 10-year event. This scale effect has been observed and discussed by other authors as well (Osborn and Renard, 1970; Wilcox, 1994).

Many factors affect relationships between rainfall and yield of runoff and sediment such that there is often no correlation between rainfall volume and runoff yield (Branson et al., 1981). Rainfall volume at our $20m^2$ plots is weakly correlated to runoff yield during the three year study, while rainfall intensity is strongly correlated to sediment yield ($p<0.005$), especially sand, for 1997 and 1998 (when the tipping bucket raingauge was in place). This suggests that total sediment yield at the $20m^2$ plots may be a reasonable indicator of runoff *intensity*. Relationships between sediment composition and sediment yield provide information about how combined rainfall characteristics (e.g., volume, intensity, duration, antecedent moisture, etc.) affect the composition of materials moving from hillslopes. Figure 2–8 shows strong negative logarithmic relationships between sediment yield and concentrations of organic C and total N, suggesting that frequent, minor rainfall events move proportionally more organic matter while infrequent larger events move more sediment, particularly sand. Figure 2-8c shows a significant positive logarithimic relationship between sediment yield and C:N ratio, suggesting selective movement of more decomposed material by minor sheetflow events.

Slope Position and Cover

The broad, gently sloping summit positions in this study are relatively stable with respect

to erosion and deposition, as indicated by well established grasses and microbiotic crusts in canopy interspaces. Litter from the mixed ponderosa pine, pinyon, juniper, and oak forests covers over 30 percent of the soil surface, but soil organic matter concentrations (as organic C, total N, and total P) are low, suggesting a lack of the fluvial mixing which occurs on lower slopes. Low soil C:N ratios suggest *in-situ* decomposition rather than removal and replacement with fresh litter. Low mineral N and P concentrations, as well as low values of available P/total P and ammonium-N/total N (Figure 2–5 and Figure 2–8) suggest tight nutrient cycles typical of stable plant communities. This type of stability, where disturbance (e.g., cultivation, fire, or dynamic erosion and deposition) is not a driving component, leads to well established soil microbial communities that rapidly immobilize inorganic nutrients so organic matter turnover rates may be high but net mineralization rates are low (Stark and Hart, 1997).

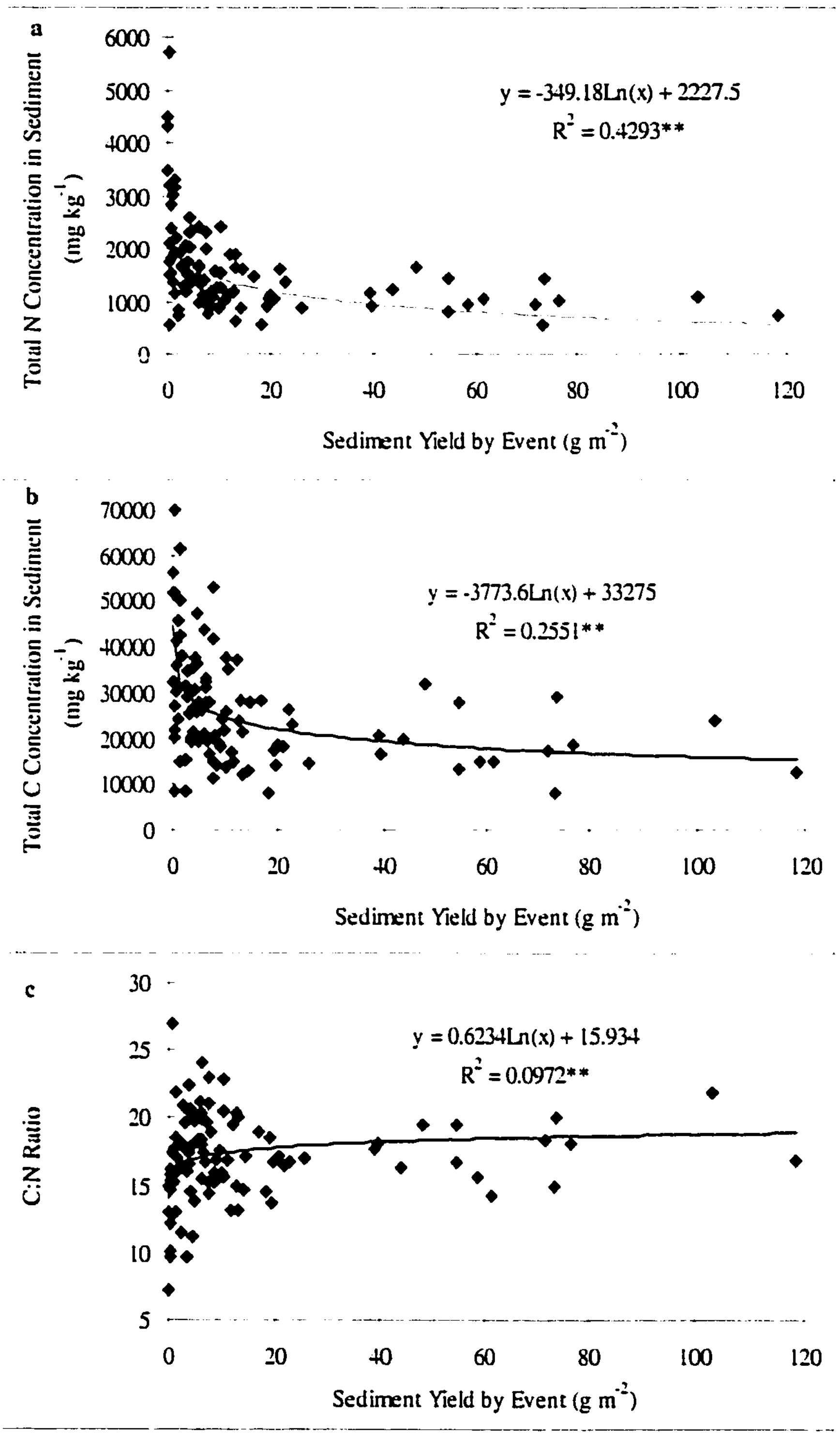

Figure 2–8. Relationship between sediment yield and concentrations of C and N in sediments. Data from all slope position plots. *,**: significant at 0.05 and 0.005

Backslopes, with steeper gradients, slowly permeable subsoils, and lack of herbaceous understory vegetation, generate runoff much more frequently than the summit positions and have much higher erosion rates. Disturbance in the form of erosion and deposition that constantly mixes, sorts, and transports soils and forest litter appears to prevent development of stable understory plant communities. Long slope lengths mean that these effects increase progressively down slope. Soil concentrations of organic C, total N, and total P are highest in the backslope positions, suggesting that slopewash processes mix forest litter with the surface soils. C:N ratios increase markedly at the top of the backslopes and then gradually decrease suggesting progressive decomposition. Rising mineral N and P concentrations, along with increasing available P/total P and ammonium-N/total N, also suggest that mineralization rates increase as forest litter decomposes and is carried down slope (Figure 2–5). These trends may reflect increasing erosive power with increasing slope length: on upper backslopes rainsplash and the beginnings of sheetflow remove forest litter as it begins to decompose so that, combined with low influx from summit positions, organic matter is dominated by fresh litter in an N-limited, immobilizing soil environment. Mineralization rates increase with decreasing elevation as partly decomposed material from upslope mixes with fresh litter deposits, possibly stimulating mineralization in a type of priming effect. This is suggested by decreasing total concentrations of C, N, and P (overall loss of organic matter) but increasing mineral N and P through lower backslope and footslope positions.

C:N ratios continue to decrease and mineral N and P increase as slope gradient decreases through footslope and toeslope positions. Herbaceous ground cover increases through these lower slope positions, probably in response to enhanced moisture and

nutrient conditions. This may lead to a more stable surface soil environment and tighter nutrient cycles, but the influx of mineralized slopewash material apparently outpaces and disrupts immobilization processes to maintain long-term productivity of the alluvial valley floor soils even where farmed for many generations (Bull, 1997; Homburg, 2000; Norton, 1996). Table 2–11 summarizes organic transformations of the hillslope system.

Table 2–11. Summary of slope position effects on organic matter transformations.

Slope position	Slope morphology, soil, and vegetation.	Organic matter transformations	Relevance/implications
Summit	Level to convex mesa tops; shallow soils with stable pinyon-juniper forest.	**Immobilization** in closed nutrient cycles of *in-situ* decomposition.	Small downslope contributions of runoff, sediment, and organic matter.
Shoulder	Convex sandstone benches and escarpments.	Litter and sand removed from bare rock surfaces.	Downslope contributions of some fresh organic matter and runoff.
Backslope	Steep straight or concave slopes; thin loamy A horizons over fine subsoils; pinyon-juniper overstory but little understory.	**Mineralization** as organic matter moves and decomposes; slope effects cause increasing perturbation (erosion and mixing) down slope.	Organic matter processing during frequent minor precipitation events contributes enriched sediments and runoff to footslopes and toeslopes.
Footslope	Gentle concave slopes; thicker A horizons over well-developed argillic horizons; mixed tree shrub, and grass plant communities.	**Mineralization** as partly decomposed organic matter from backslopes sustains productive plant community in otherwise stable position.	Soil fertility, moisture, and tilth is renewed by interception of processed organic matter and sandy sediments.
Toeslope	Level to gently sloping sagebrush dominated alluvium that doubles as toeslope in hillslope system and alluvial terrace in valley floor fluvial system.	**Mineralization** in fresh deposits; **immobilization** in stable positions where rill erosion precludes inputs of fresh slope wash (runoff bypasses position).	Frequent minor precipitation events deposit fine sediments as sheet wash from adjacent slopes infiltrates toeslope soils. Organic matter and coarser sediment mostly caught on footslopes.

Seasonality

Figure 2–9 suggests that these organic matter dynamics change somewhat through the thunderstorm season. Considered in the context of Zuni's annual precipitation pattern, these data may indicate pulses of organic matter decomposition and movement at the beginning of the runoff season.

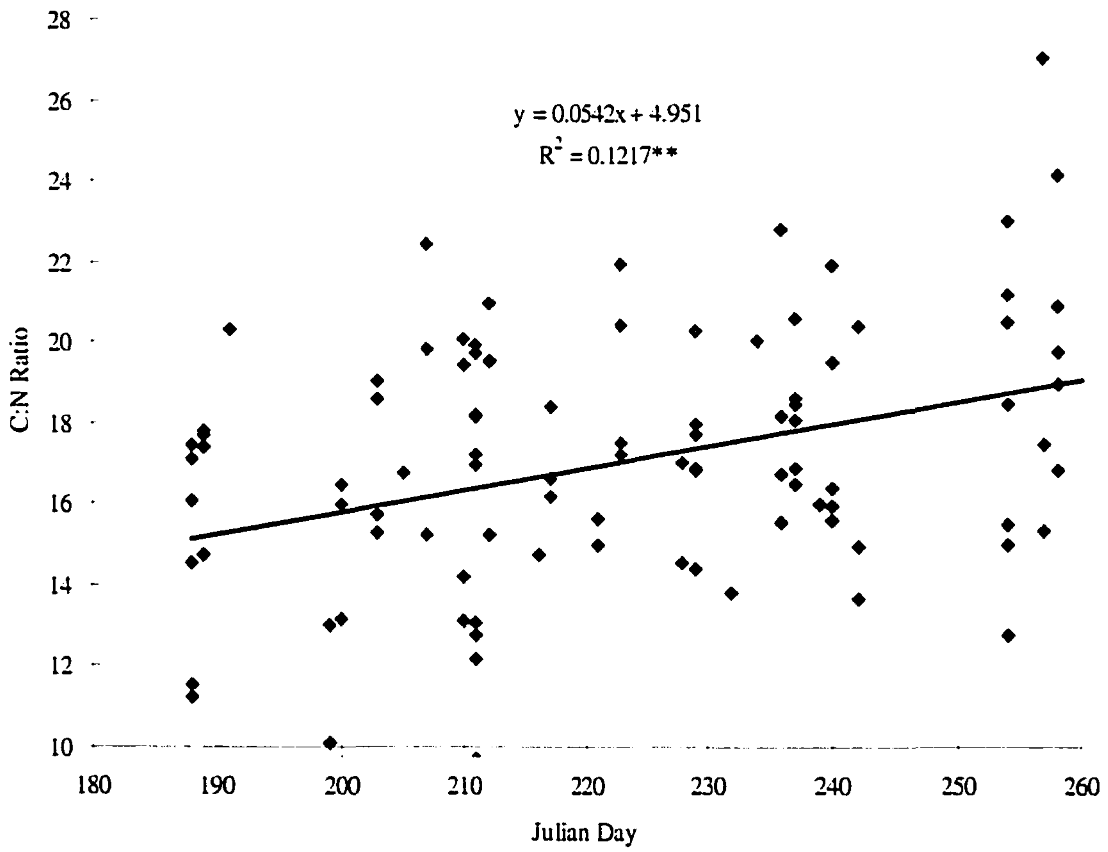

Figure 2–9. 1996-1998 sediment C:N ratios from $20 m^2$ runoff plots plotted against Julian day of storm. Yields of total sediment, organic matter, and particle size distribution do not follow significant trends with respect to date.

Winters at Zuni are characterized by cold nighttime temperatures, daytime temperatures above freezing and often quite warm, and precipitation in the form of low intensity rain or snow from frontal systems that generate little runoff (Tuan et al., 1973).

This combination probably creates prolonged moist conditions and frequent freeze-thaw cycles that accelerate both physical and microbial breakdown of forest litter (Honeycutt, 1995). Warmer daytime temperatures in spring intensify freeze-thaw effects and bring about wetting and drying cycles that also enhance decomposition (Cui and Caldwell, 1997). Early summer is typically hot and dry so that surface soils and organic debris become desiccated. This winter-spring-early summer pattern, with prevalent moist freeze-thaw conditions followed by pronounced desiccation, may result in accumulation of physically decomposed organic matter on hillslopes. Wilcox (1994) reports a similar seasonal effect: erodibility of soils in pinyon-juniper interspaces is highest at the end of the winter freeze-thaw cycles and lowest at the end of the summer rainy season. The first summer rains, usually in July, bring a pulse of mineralization that is reflected in the lower C:N ratios of early season sediments. As the rainy season progresses, with frequent, gentle runoff events, the slopes become more and more depleted of decomposed (low C:N) material.

CONCLUSIONS

The results of this research provide a basis for understanding watershed hillslope characteristics that contribute to sustained productivity of semiarid alluvial soils. Relationships between soil, landform, and vegetation patterns point to the forested backslopes as a driving force behind movement and processing of runoff, sediment, and organic matter. Backslopes' large areal extent, steepness, slowly permeable subsoils, and combination of bare soil and tree species that produce large amounts of forest litter produce sandy sediments and organic matter ultimately responsible for favorable hydrological properties and fertility in alluvial fields.

Rainfall patterns dominated by minor events that generate short-distance sheet flow create an excellent organic matter processing system that stimulates mineralization as it mixes materials and carries them downslope. Less frequent flushing flows move accumulated sediments and organic matter from lower slopes to alluvial landforms where traditional agricultural fields are typically located.

Traditional alluvial fan farming remains an important cultural activity among the Zuni and other Southwestern Native American Tribes (Manolescu, 1995; Nabhan, 1984; Norton et al., 1998; Pawluk, 1995), but the importance of hydrological connectivity between upland hillslopes and alluvial landforms extends beyond its value to traditional agriculture. Sediments, organic matter, and runoff from hillslopes are valuable resources for sustaining ecological diversity and productivity in flood plains, riparian areas, alluvial fans, and downstream aquatic systems. Functional flood plains and alluvial fans store sediments, attenuate peak flows, and absorb runoff which can maintain down stream perennial flows. Without functional hydrological connectivity (due to channel incision or channelization) products of hillslope erosion are lost to alluvial landforms and become environmental liabilities in a feedback spiral of soil degradation where sediments and constricted flows damage downstream aquatic systems (Bull, 1997).

This research improves understanding of the hillslope component of the connection between upland slopes and alluvial soils on the Zuni Indian Reservation. The fluvial system that transports hillslope materials is the subject of chapter three and nutrient dynamics within alluvial fans of chapter four.

Chapter 3: Organic matter transformations in discontinuous ephemeral streams

INTRODUCTION

Ephemeral stream channels that link upland mesas and canyons to alluvial fans may have important detritus-processing functions that contribute to alluvial fan soil fertility. While detritus-processing ecology of perennial streams is well understood (Boling et al., 1975; Maltby, 1992), those functions of ephemeral systems in semiarid regions have received little attention, even though they form a major portion of the world's water resources (Davies et al., 1994). Better understanding of how ephemeral stream systems contribute to alluvial fan productivity could improve our ability to conserve and restore these key landforms in degrading semiarid landscapes. Traditional runoff agricultural fields that continue to produce crops even after centuries of cultivation (Damp and Kendrick, 2000) utilize alluvial fans of small upland watersheds.

Schumm (1977) presents a simplified model of a river system that has three primary zones relevant to both perennial and ephemeral streams (Figure 3–1). While processes differ somewhat between perennial and ephemeral systems, a review of detritus processing ecology in perennial streams is useful to understanding general principles common to both systems. Generally, perennial streams are characterized by cascading processes where primary inputs of leaf litter are progressively decomposed and the fine-particulate products moved down stream. The particle size and C:N ratio of organic detritus decrease in a downstream direction while its recalcitrance increases (Wagener et al., 1998). In the headwaters "production zone" of perennial streams, fresh forest floor leaf litter is the primary source of energy for microbial decomposers and invertebrate

processors. Leachates and fine, "processed" organic matter are washed downstream to the "transfer zone" where fresh inputs of forest litter are minimal and living primary producers make up a large portion of the biomass. Decomposable C is lost through microbial respiration while N is immobilized (Petts, 1994; Wagener et al., 1998). In the "storage zone" fine textured, recalcitrant organic matter from upstream is the primary source of C and nutrients. This material may be stored as humus in floodplain or alluvial fan soils.

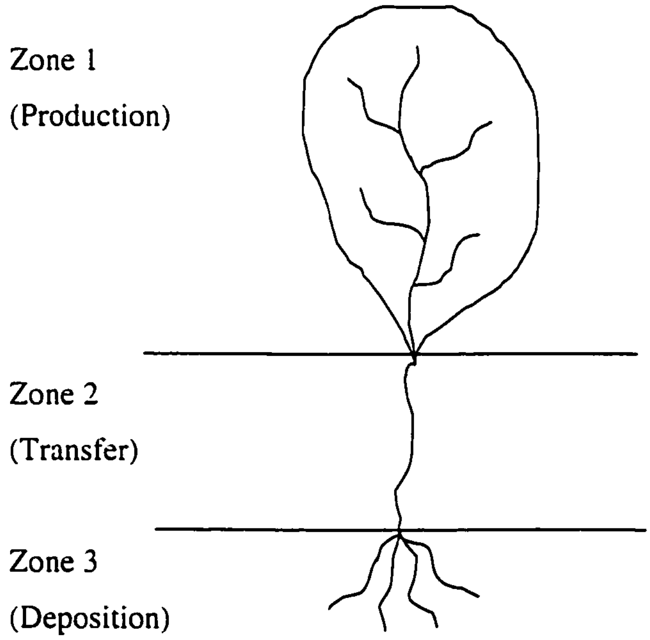

Figure 3–1. Idealized fluvial system (after Schumm, 1977, and Petts, 1994) Zone 1 corresponds to the "canyon reaches" of the Weekoty and Sanchez arroyos, Zone 2 to the "arroyo reaches," and Zone 3 to the "fan reaches" (see map; Figure 3-2).

These longitudinal processes along stream courses refer primarily to base flow conditions in perennial streams; conditions that do not exist in ephemeral channels which, by definition, are higher than ground water tables at all times (Bull, 1997). Davies et al. (1994) define ephemeral streams as those that flow less than 20 percent of the time and only in response to unpredictable rainfall. They speculate that, in the absence of aquatic detritus processors which dominant decomposition in perennial streams, physical breakdown, leaching, and microbial respiration may be the most important factors in processing organic detritus. In fact, studies of flood pulse responses in dryland rivers show that detrital decomposition and nutrient cycling are fastest in aerobic flood deposits such that subsequent periods of submergence and exposure facilitate mineralization and increase productivity. Temporary wetlands, for instance, are often more diverse and productive than those subjected to prolonged drying or prolonged inundation (Davies et al., 1994).

The hydrology of dryland ephemeral streams is characterized by extreme variability where coefficient of variations (CV's) for annual discharge often exceed 100 percent. While as much as 60 percent of the total sediment load of ephemeral streams may be transported by events with return intervals greater than 10 years (Davies et al., 1994), the frequent wetting and drying of low-flow or no-flow precipitation events may be responsible for the majority of detrital decomposition. Therefore, the high frequency, low magnitude events may behave much like base flows in perennial streams, supporting the cascade of decomposition and transport processes described by Wagener et al. (1995). They differ from perennial base flow processes in that physical breakdown from wetting-drying cycles and aerobic microbial respiration are more important than processing by

suites of aquatic organisms. Organic detritus processed in this manner is ultimately transported to alluvial fans by lower-frequency, higher magnitude events.

The extreme variability in rainfall and streamflow of drylands leads to alluvial landforms subject to rapid and major change. Alluvial fans with soil forming processes dominated by inputs of sediment and organic detritus can become rapidly incised and excluded from the "storage zone," becoming instead dry terraces bounding the "transfer zone" (Bull, 1990). Such sudden exclusion from the fluvial system drastically alters soil forming processes and brings changes in plant communities and hydrological behavior. Incision often causes conversion from grass-forb dominated alluvial soils to deep-rooted woody vegetation that decreases hydraulic roughness, increasing runoff and further promoting incision (Bull, 1997). Comparison of incised (terrace) and unincised (alluvial fan) soils may provide insight into soil processes that support long-term agricultural sustainability as well as effects of incision on soil biological and hydrological processes and plant community composition.

In this chapter I report investigations of processes that transport and transform organic matter through two small scale ephemeral stream systems, how rainfall patterns impact those processes, and how arroyo incision changes nutrient cycling in alluvial soils. Arroyo cutting during the twentieth century transformed fluvial systems by creating continuous channels where runoff previously spread over broad alluvial fans and flood plains (Balling and Wells, 1990; Cooke and Reeves, 1976; Graf, 1988). Many of the smallest, headwater watersheds that rise on forested bedrock uplands and empty onto margins of alluvial valleys, remain unincised but are threatened by headcuts working up from incised water courses below or by concentrated flows that scour channels within

(Bull, 1997; Lagasse et al., 1990). These small-scale watersheds are crucial to ecological and hydrological functionality in semiarid landscapes and are easily protected by structural or watershed management approaches (DeBano and Heede, 1987; Gellis et al., 1995). Information about how linked hydrological and biological processes and renew alluvial soils in these watersheds, and the nature of resources lost with channel incision, could improve conservation efforts on these important and vulnerable landforms.

MATERIALS AND METHODS

Site Description

I analyzed soil, sediment, and fluvial detritus properties along channels from watershed divides to distal alluvial fans in two watersheds above long-term traditional alluvial runoff agricultural fields (Figure 3–2). The Sanchez watershed drains 68 ha about one km south of the small farming village of Pescado, near the eastern edge of the reservation and the Weekoty watershed drains 125 ha between Pescado and Nutria. Each of the watersheds is characterized by steep-walled canyons cut into sandstone and shale members of the Gallup Sandstone (Anderson et al., 1989). Layered shale and sandstone members underlie "mesa top" positions, thickly bedded sandstone creates fall faces, thick, weathered shale underlies transportational midslope and colluvial footslope positions, and sandy alluvium forms alluvial toeslopes. The canyon-floor alluvium in each watershed is bisected by an arroyo ranging up to 6 m deep. In each case the arroyo channel ends above a runoff agricultural field, near the canyon mouth.

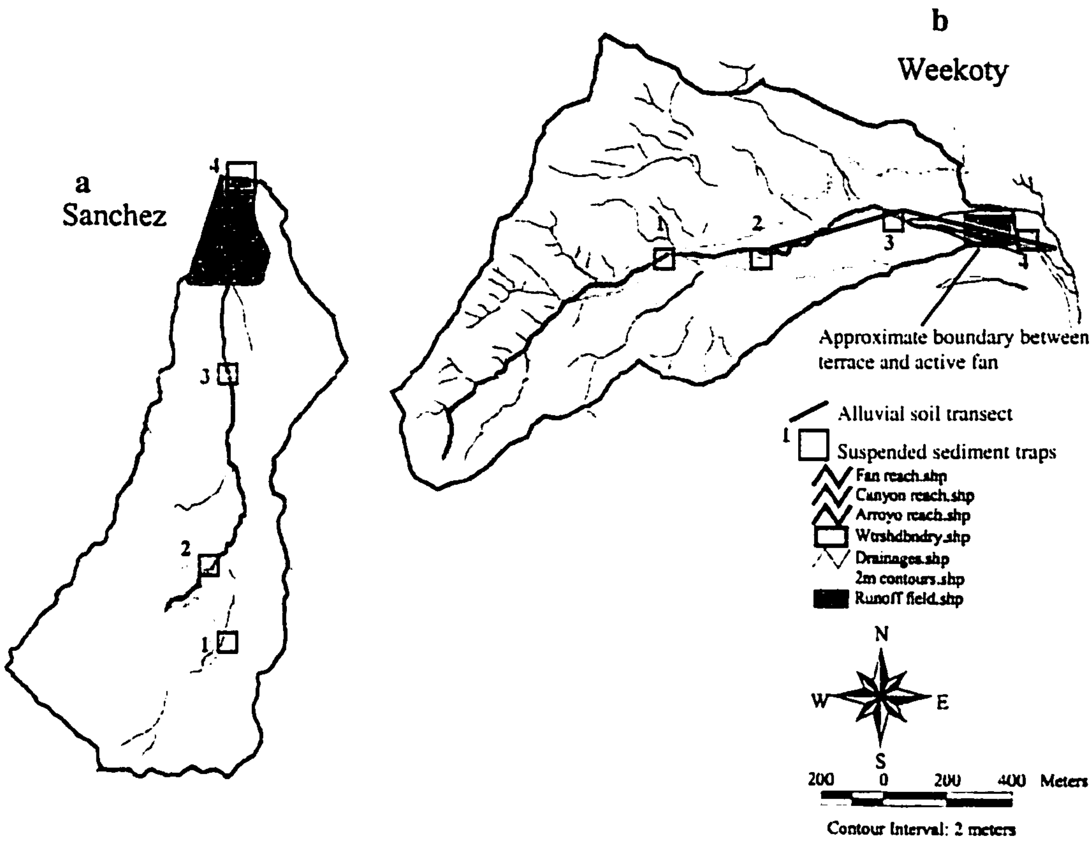

Figure 3–2. Study watersheds showing arroyo reaches, suspended sediment trap locations, and Weekoty alluvial soil transect location.

Field and Laboratory Procedures

Fluvial Organic Detritus

I analyzed effects of fluvial transport on forest litter by collecting samples of water-deposited forest floor detritus in stream channels. Samples from organic detritus accumulations were collected along 15 m reaches each 100m from arroyo source to distal alluvial fan (samples from each detritus clump 7.5 m upstream and 7.5 m down from the 100 m point). These samples were mixed in a bucket and collected a subsample. Organic matter accumulations were somewhat scarce in the lower reaches of the alluvial fans, forcing us to collect organic matter samples opportunistically and note locations (as meters from source) along channel trajectories.

Organic matter samples were air dried in the field and then analyzed for concentrations of total C and N in subsamples ground to pass a 76μm sieve using a Fissions EA1100 dry combustion CNSHO analyzer (Fissions Inst., Inc., Milan, Italy). Total phosphorus concentrations were determined by alkaline oxidation (Dick and Tabatabai, 1977). Available phosphorus concentrations were measured by the Olsen extraction method (Olsen and Sommers, 1982). Ammonium- and nitrate-N concentrations were determined in 2*M* KCl extracts using the Berthelot reaction (Willis et al., 1993) for ammonium-N and nitration of salicylate (Yang et al., 1998) for nitrate-N.

Suspended Sediments

Movement and transformation of fine organic particulate transported in ephemeral stream flows were analyzed by sampling suspended sediments below four reaches of each arroyo system (Figure 3–2). Samples were collected during the summers of 1997 and 1998 in the Weekoty and during 1998 in the Sanchez watershed. Samplers were based on USGS samplers designed to collect runoff during rising stages of runoff events. Each USGS sampler consists four or more 1 L sample bottles stacked inside 4 inch (10.16cm) ID PVC pipe, each with an inlet tube piercing the upstream side of the PVC pipe and a vent tube extending out the top of the pipe. The samplers were modified to fit the scale of the small channels at our study sites by stacking two 1 L bottles and burying the encasing PVC pipe in the center of channel bed, leaving about 15 cm exposed. Inlet tubes were 1 cm and 5 cm from the channel bed surface. Samples were collected after each runoff event, preserved with dilute phenyl mercuric acetate solution, and allowed to settle in refrigerators at 4°C. Total volume of each sample was recorded and clear supernatants were analyzed for cation concentration by atomic absorption

spectrophotometry and anion concentration with a Tecnicon AutoAnalyzer. Sediment samples were air-dried (oven temperature 60°C), weighed for calculation of sediment concentration, and analyzed for total C, N, and P by methods described above for organic detritus. Samples were generally too small for analyses of mineral N and P fractions or particle size distribution.

Precipitation volume, intensity, and duration was measured only at the Weekoty watershed at a tipping-bucket raingauge and a CRX-20 data logger (Campbell Scientific, Inc., Logan, UT) located near sediment trap #3 in the Weekoty watershed (Figure 3–2).

Alluvial Soils

Effects of active alluvial deposition on soil properties were analyzed by collecting soil samples along a transect extending through incised and active portions of the lower Weekoty watershed (Figure 3–2). Three plots on perpendicular transects were sampled each 30 m along the axis. The three points were located at random distances along the secondary, perpendicular transects. Points that fell within the bed or banks of the bisecting arroyo channel were moved 10 m in the direction of the closest terrace surface. Areal soil cover (bare soil, coarse fragments, and vegetation) was sampled in a 1 m^2 frame (Daubenmire, 1968) and collected one 15 cm depth bulk soil sample from within the cover plot. Soil samples were collected by subsampling the mixture of at least five samples collected within the 1 m^2 plot. Samples were air-dried in the field and transported to laboratories for analyses. Soil physical and chemical properties, including particle size distribution, total C, total N, total P and available P were determined in the laboratory. Particle size distribution was determined using the sieve and pipette method (Gee and Bauder, 1986), with samples pretreated with a 30 percent hydrogen peroxide

reagent for organic matter digestion and a sodium hexametaphosphate solution for clay dispersion. Total C, N, and phosphorus and available phosphorus concentrations were determined as described above for organic detritus. Inorganic C concentration was determined with a coulombmeter on a subset of samples and found to be insignificant relative to total C concentration, therefore, total C content is assumed to be identical to organic C content for the analyses.

RESULTS

Fluvial Organic Detritus

Regression analyses show that concentrations of total C, N, and P, as well as available N and P, in the organic detritus samples change along distinct parabolic trends through Weekoty and Sanchez fluvial systems (Figure 3–3). Available N concentration, both ammonium- and nitrate-N (only nitrate-N is presented), increases distinctly with distance from source at the Weekoty arroyo but not at the Sanchez arroyo. Phosphorus contents, both total and available, follow especially tight parabolic trends along the channels.

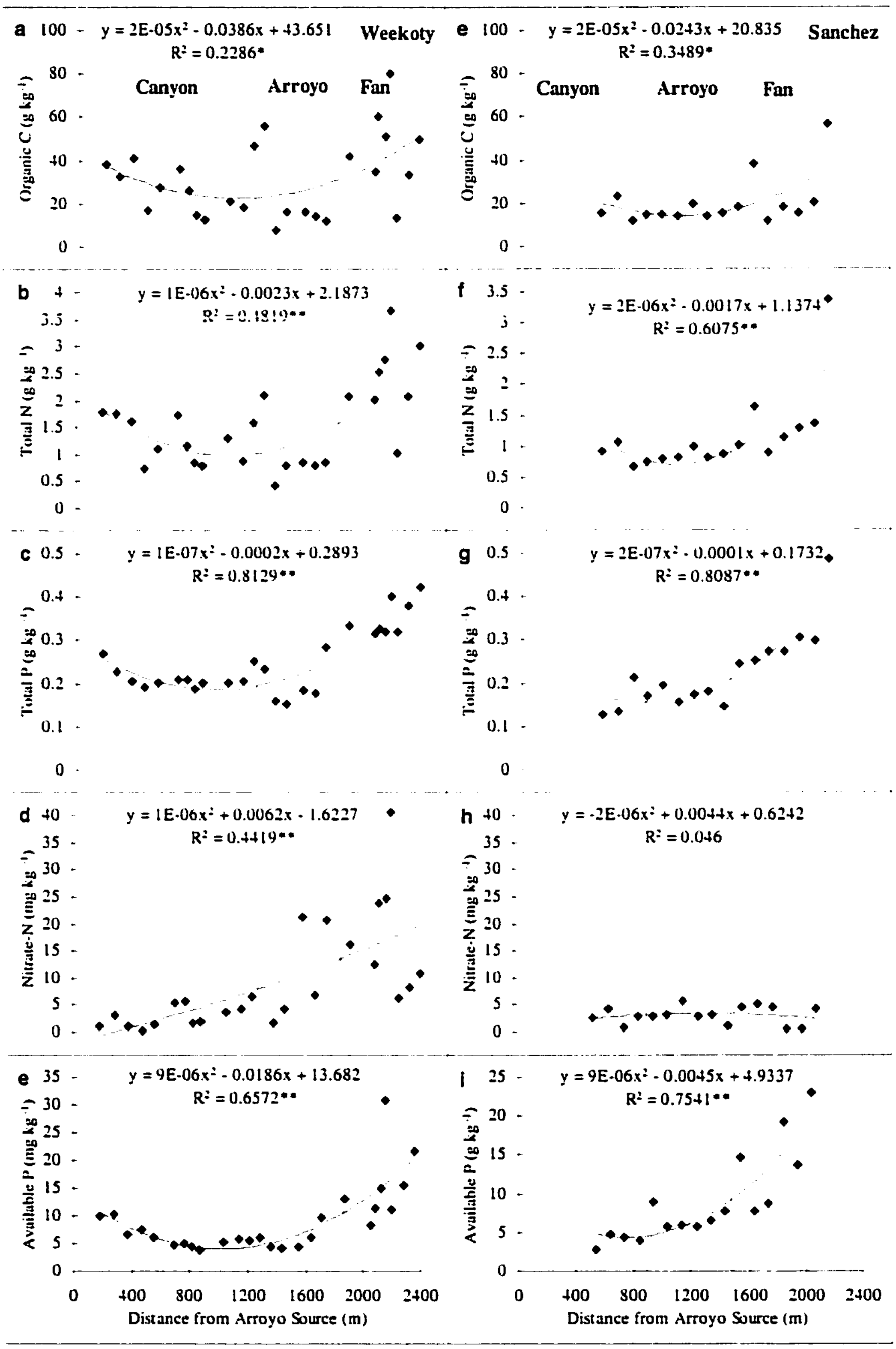

Figure 3–3. Organic detritus composition as a function of distance from arroyo source. Sampling of the Sanchez arroyo began approximately 500m from its source. *,**: significant at 0.05 and 0.005 levels respectively.

Relationships between the C, N, and P fractions are similar between the two study sites (Figure 3–4). Carbon to N ratios are variable but decrease significantly in a downstream direction along the channels. Available P as a percent of total P closely follows polynomial trends as functions of distance from watershed divides. The ratio of ammonium-N to nitrate-N, an indicator of nitrification rates, is relatively high and variable in the canyon reaches of the Weekoty system, but very constant at about one to one in the arroyo and alluvial fan reaches. Nitrate-N as a proportion of both total N and organic C increases with distances from the source at the Weekoty arroyo.

Suspended Sediments

Runoff samples were collected from the Weekoty arroyo after nine events in 1997 and 1998 and from the Sanchez arroyo after four events in 1998. While each trap received runoff during most of the events, it did not always appear to be the result of continuous flow from upper canyons to distal channel fans. Observations during sample collection suggest that flow intensity peaks where canyon reaches empty into arroyo reaches. There was considerable scour at these traps (trap #2 at each site; Figure 3–2) after several of the events in each watershed. Transmission losses through the sandy arroyos appear to rapidly diminish flows. The most distal trap at each site did not receive runoff during several of the events, and during others runoff came from local sheet flow. Some the events in each watershed did generate continuous flow past all the traps. Most of our samples came from bottles connected to the lower intakes, 1 cm above ground level, and probably represent the very beginning of flow at the traps. Interestingly, samples from both intake depths were essentially identical. They are lumped for the data reported here.

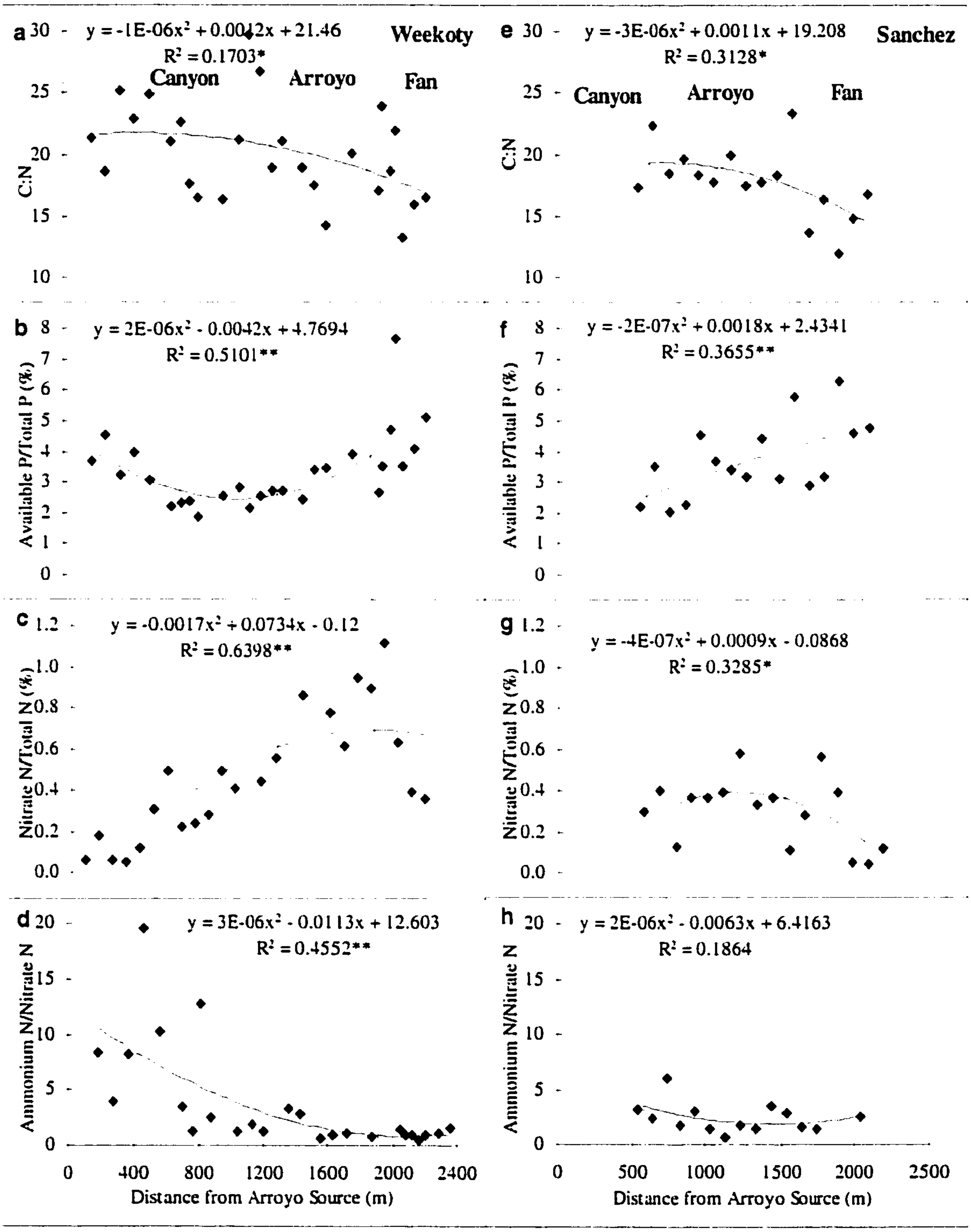

Figure 3–4. Relationships between total and available nutrients and stream course position in organic detritus. *,**: significant at 0.05 and 0.005 levels respectively.

Suspended sediment concentrations in the runoff samples are highly variable and range from 0.6 to 128 g l^{-1} without predictable differences between sediment trap locations. Sediment concentration increases with increasing rainfall intensity, however, (Figure 3–5) and C to N ratios in the fine organic particles increase with increasing sediment concentration (Figure 3–6).

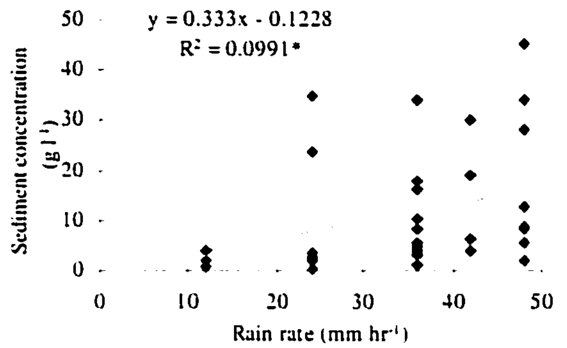

Figure 3–5. Sediment concentration as a function of rainfall intensity as measured at Weekoty suspended sediment traps and tipping bucket rain gauge.

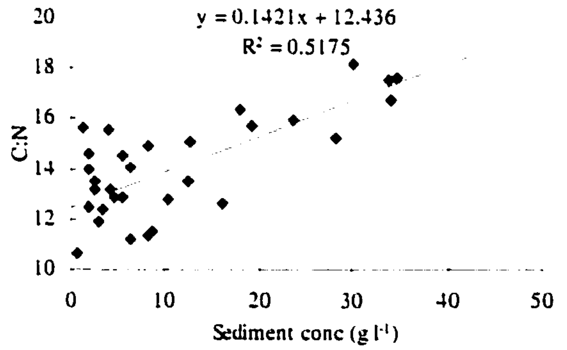

Figure 3–6. C:N ratio of sediment organic matter as a function of sediment concentration at Weekoty suspended sediment traps.

Though sediment concentration in runoff varies greatly among events and trap locations, concentrations of total C, N, and P in the sediments remain relatively constant among events and appear to vary systematically among traps (Figure 3–7). Each of these organic matter constituents decrease between trap 1 (upper canyons) and trap 2 (lower

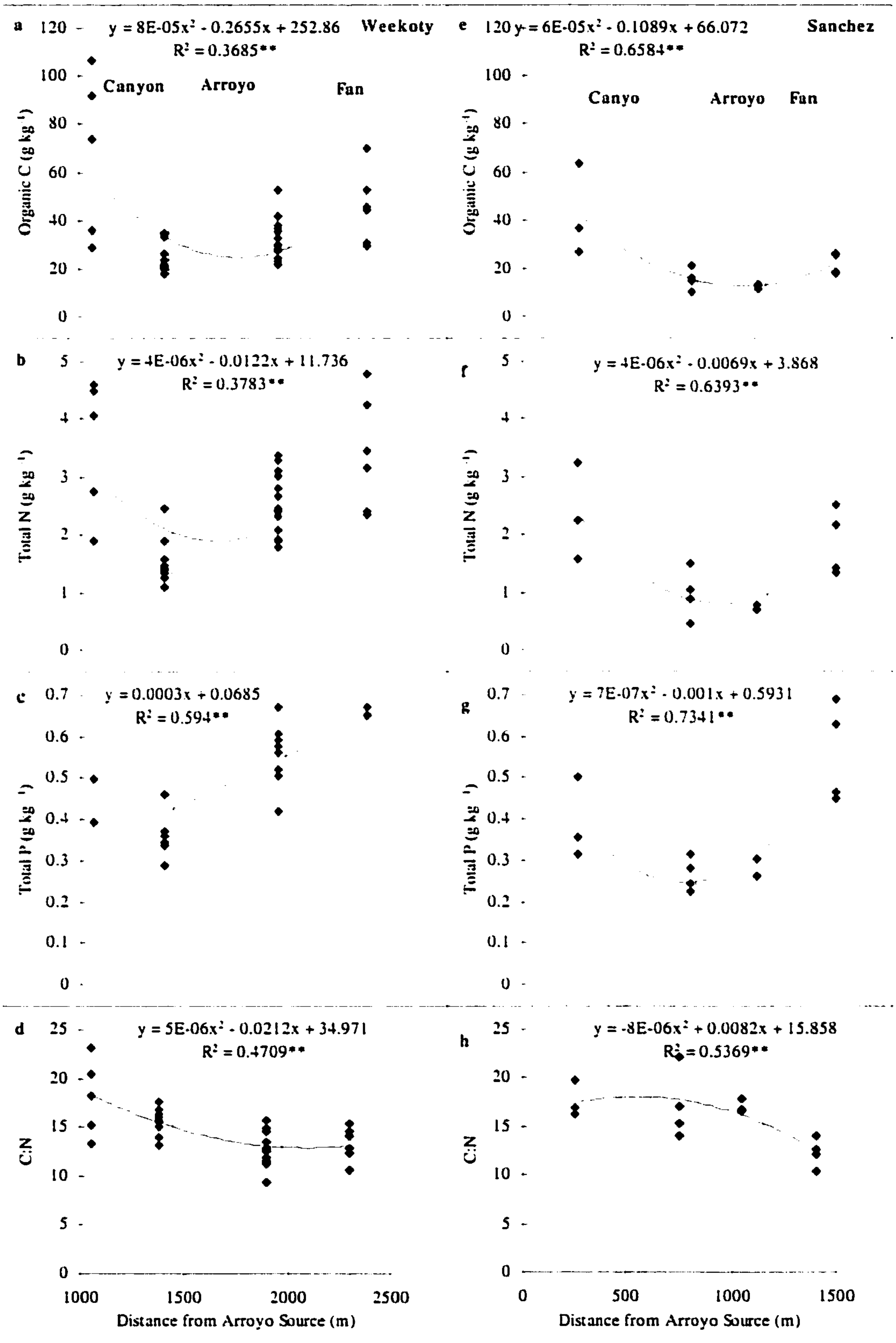

Figure 3–7. Concentrations of organic C, total N, and total P as function of arroyo position. *,**: significant at 0.05 and 0.005 levels respectively.

canyons) and then increase at least slightly at trap 3 (arroyo mouths) and again at trap 4 (distal alluvial fans). Carbon to N ratios in sediments decreases between the upper and lower traps at both sites, with the largest difference occurring between traps 2 and 3 at the Weekoty site and traps 3 and 4 at the Sanchez site.

Alluvial Soils

Changes in particle size distribution, pH, and organic matter along the alluvial soil transect follow bimodal trends that change at the boundary between the incised alluvial terrace and active alluvial fans (about 600 m from the proximal terminus of the alluvium) (Figure 3–8). The most notable changes between upper and lower Weekoty transects are abrupt increases in sand content, decreases in C, N, and P concentrations, and indications of higher mineralization rates (sharp decreases in C to N ratios and increases in available P relative to organic C). The upper portions of the transects (0-600 m) are generally stable alluvial terraces with well established big sagebrush-blue grama plant communities that are probably influenced by materials eroded from adjacent hillslope systems. The terraces of the upper transects form toeslopes of adjacent hillslope systems. Lower portions of the transects (600 m+) cross alluvial fans that receive materials from the fluvial system and are more sparsely vegetated by weeds and pioneer species.

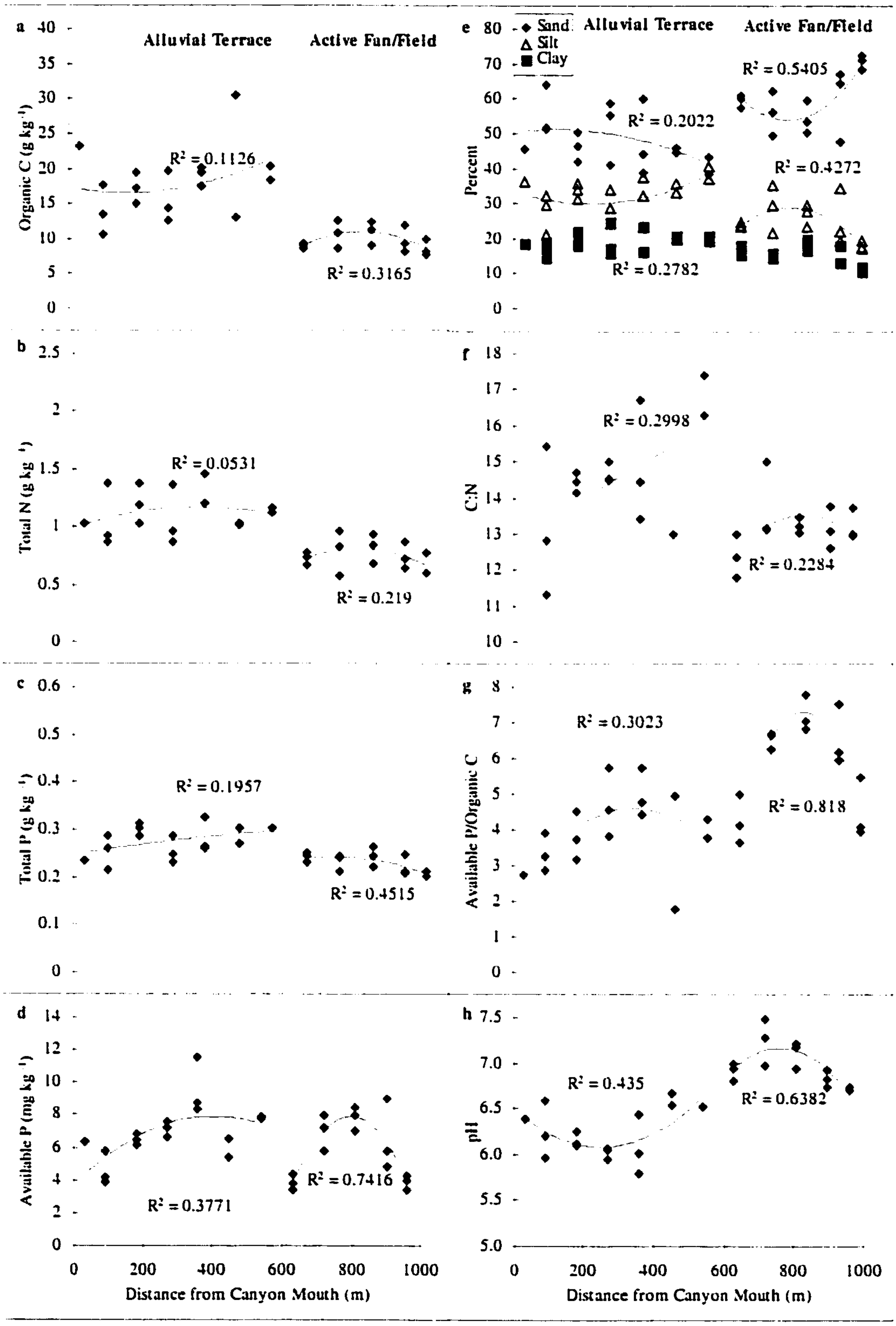

Figure 3–8. Properties of alluvial soils as function fan position, Weekoty watershed alluvial soil transect (see Figure 2 for location).

DISCUSSION

Organic Matter Movement and Transformation

The combination of rainfall intensity, sediment concentration, and organic matter/nutrient contents of sediment suggest relatively frequent, low intensity runoff events preferentially move more highly decomposed organic materials. This pattern (materials being moved downstream as they are broken down) is known to be important in organic detritus processing by perennial streams (Boling et al., 1975; Maltby, 1992; Wagener et al., 1998). Just as for perennial streams, our data suggest that dominant processes transforming organic matter vary by reach depending on the amount and composition of materials entering the stream from surrounding slopes. Table 3–1 summarizes effects by channel reach and Table 3–2 summarizes effects of different types of rainfall events.

In upper canyon reaches (1st order) on relatively level mesa tops, gentle slope processes contribute to conditions that stimulate nutrient immobilization in decomposing organic matter. Forest floor materials under relatively level, mesa top woodlands decompose *in-situ* which, together with lower intensity runoff (because of shorter, flatter slopes) that minimizes disturbance, leads to relatively stable plant and microbial communities, rapid immobilization, and "tight" nutrient cycles (Stark and Hart, 1997). This is suggested by low available N and P concentrations in the organic detritus of canyon reaches. Gentle runoff on the short, relatively level slopes preferentially moves partly decomposed materials to channels. As this material is decomposed and moved downstream into lower canyon reaches (2nd to 4th order), it mixes with large quantities

of relatively fresh, high C content, forest floor material from longer, steeper slopes forested by ponderosa pine, Gambels oak, and pinyon-juniper. This influx of C-rich forest litter probably stimulates immobilization in organic detritus of lower canyon reaches (relatively high C to N ratios and low available P/total P). However, steep gradients and convergence of many tributaries through these reaches appear to create relatively high stream power, even during high frequency, low magnitude events. This frequent perturbation probably leads to a relatively "open" N cycle suggested by increasing inorganic N concentrations in the detritus.

Table 3–1. Summary of watershed zone effects on organic matter transformations.

Watershed Zone (after Schumm, 1977)	Watershed and Fluvial System Characteristics	Organic Detritus Contributions/Processing	Relevance/implications
Production Zone			
1st order	Mesa tops: stable mixed forest, shallow rill-like channels.	Mixed decomposed and fresh forest litter; infrequent channel flow.	Mineralization due to relatively low input of fresh material and frequent wetting-drying without sorting flows.
2nd to ~4th order	Canyons: steep, forested slopes; little ground cover vegetation; narrow, bedrock bed channels; maximum stream power.	Mostly fresh, high C content forest litter; frequent minor channel flow selectively removes decomposed material.	Immobilization due to large influx of forest litter and frequent removal of fine, decomposed components.
Transport Zone	Arroyos: narrow, incised alluvial channels.	Influx mainly from channel; transmission losses decrease flows.	Mineralization due to reduced direct input of fresh material and accumulation of fine, decomposed material due to channel inflitration.
Storage Zone	Alluvial fans: sandy alluvium; depositional, distributary channels.	Occasional low-energy influx of fine sediment and decomposed OM; main influx from infrequent flood events.	Mineralization due to infrequent influx of fresh material and frequent wetting-drying in sandy soils.

Table 3–2. Summary of rainfall/runoff characteristics and effects.

Frequency	Rainfall	Runoff	Impacts
High (~50 times/summer season)	low intensity; <15mm d^{-1}	none, or minor hillslope	frequent wetting, drying, and mixing of hillslope sediments and organic matter.
Moderate (10-20 times/season)	low to moderate intensity; 15-25mm d^{-1}	hillslope runoff and low energy, discontinuous channel flow	transport of hillslope sediments and organic matter to channel; downstream movement of fine-particulate organic detritus.
Low (2-5 yr return interval)	High intensity; >25mm d^{-1}	channel- and fan-shaping flushing flows with relatively large amounts of sandy, bedload sediments	scour channels and deposit fresh loads of sandy sediment and mixed organic detritus on alluvial fans. Tailing arm may cause fill equal to or greater than scour from peak.

The influx of fresh material from side slopes stops abruptly as channels emerge from canyons and enter arroyos cut through alluvial valley fills. Runoff intensity peaks at this transition from steep bedrock channels to more gently sloping alluvial channels. The relatively high stream power is reflected in low C, N, and P concentrations and high C to N ratios in suspended sediments (low density, decomposed organic matter is preferentially removed by the flowing water). Essentially, flows emerge from the forested bedrock canyon rich with both suspended sediments and organic detritus. Sediments are deposited as stream gradient decreases, but the low-density detritus is carried farther downstream and deposited as transmission losses diminish flows across the sandy channel beds. Each flow mixes, moves, and sorts the organic detritus causing increasing mineralization rates through arroyo reaches. The predominance of low flows from minor rain events preferentially move fine, low C to N ratio particles downstream.

Alluvial fans receive influxes of coarse organic detritus only during low

frequency, intense runoff events that deposit loads of sandy sediments across valley floors. Some of the more frequent low intensity runoff events also move across alluvial fans, but deposit only fine sediments and relatively highly decomposed fine particulate organic matter. This combination of wetting by frequent low intensity rain events, occasional influx of low C:N organic particles, and lack of coarse forest detritus influx contributes to increasing mineralization rates in organic detritus deposits with distance through the alluvial fans. Sala and Lauenroth (1982) emphasize the importance of frequent small rainfall events in driving organic matter dynamics in semiarid soils.

Figure 3-4d suggests nitrification in organic detritus of the forested canyon reach may be inhibited. White (1994) describes a mechanism for this type of inhibition in Southwestern conifer forests by volatile organic compounds called monoturpenes. This effect appears to diminish as organic detritus is moved farther from its source on the ponderosa pine forested slopes, possibly because the volatile compounds are lost as materials decompose.

Differences between mineral N concentrations in organic detritus from the Weekoty and Sanchez arroyos (Figure 3-3), along with similarities in organic C, total N, and total P concentrations seem to suggest greater N immobilization in all the Sanchez samples and may reflect differences in sampling times or inadvertent differences in handling of samples (i.e., the Sanchez soil were wetter at sampling and humid weather caused them to air-dry slowly).

Soils of Active Alluvial Fans and Incised Alluvial Terraces

Results from analyses of soils and vegetation on incised alluvial terraces and the active alluvial fan at the Weekoty watershed indicate that arroyo cutting may cause sharp

changes in pedogenic processes that drive soil productivity and nutrient cycling. Arroyo cutting converts dynamic alluvial fan surfaces, where ephemeral storm water flows dominate fluvial and soil processes, to stable alluvial terraces removed from the active fluvial system. Instead of alluvial fans, the terraces function as toeslope members of valley wall hillslope systems, so differences in pedogenic processes result from conversion of dynamic alluvial fans to relatively stable alluvial toeslopes.

The predominance of low intensity hillslope runoff may explain relatively fine-textured soils (loams) on the terrace toeslopes compared to the sandy loams and loamy sands on active alluvial fans (Figure 3–8). The close relationship between organic C content and particle size in alluvial fan soils, especially its higher correlation with silt than clay ($r = 0.906$ and 0.578, respectively), suggests that the fluvial processes that drive particle size distribution on alluvial fans also drive organic matter content. This relationship (higher correlation of organic C with silt than clay) was also noted by Homburg (2000) in his analysis of 30 alluvial fans on the Zuni Reservation. On the terraces, lower correlation coefficients between particle size and organic matter suggests that organic matter content and transformation may be less a function of fluvial processes than of cycling within the well developed sage brush-perennial grass plant communities.

Stable, well developed plant communities, like that of the terrace soils, generally have efficient nutrient cycles where diverse soil microbial communities compete intensely with plants for inorganic nutrients and net immobilization dominates organic matter turnover processes (Stark and Hart, 1997). This scenario is indicated in the terrace soils by relatively high organic matter content (reflected in total C, N, and P concentrations) but relatively low available P concentration, both absolute and as

percentages of total P and organic C; suggesting that organic matter turnover rates are limited by intense competition for available nutrients.

Disturbance-driven systems, on the other hand, undergo perturbations that impede uptake and immobilization while they stimulate decomposition, resulting in a C-limited environment and net mineralization (Pickett et al., 1989; Schimel, 1986). This scenario is indicated in active alluvial fan soils where occasional intense floods scour and redeposit alluvial sediments. Soil organic matter content (as indicated by total C, N, and P concentrations) is generally lower than that of the terraces but available P concentration is equal or somewhat higher. Mineralization rates appear to be considerably higher in the alluvial fan soils, however, because C to N ratios are significantly lower and available P as a proportion of organic C is generally higher in alluvial fan soils than terrace soils.

Soil pH also varies considerably between terrace and alluvial fan soils. Low pH levels in terrace soil probably result from the dearth of soluble inorganic nutrients. These pH levels generally favor microbial communities dominated by fungi, which are generally active immobilizers and indicate relatively stable soil environments (Killham, 1994). Soil pH levels in alluvial fan soils suggest more soluble salts of plant available nutrients and favor mineralizing bacterial communities.

CONCLUSIONS

Our results document ephemeral stream processes that link watershed hillslopes to ecologically important alluvial fans. Ephemeral stormwater flows that scour channels transport and deposit fresh loads of sandy sediments and are important drivers of hydrological functions of alluvial fans. These relatively high impact events shape the fluvial system and have received a great deal of attention. Our results show that minor

rainfall and runoff may drive biochemical processes that link forested watersheds to alluvial fans. In contrast to dramatic, bedload-transporting events that have multi-year average return intervals, minor low-energy flow events generally occur multiple times during the summer rainy season. These minor events repeatedly moisten, mix, and sort channel and hillslope materials as they move them downstream in a stepwise fashion. This results in mineralization rates that increase through the fluvial system and accumulation of decomposed, nutrient-rich organic matter in lower reaches.

Schumm (1977) divided fluvial systems into generalized zones with distinct impacts on hydrology and geomorphology and important implications for ditritus processing in perennial stream ecology. Our results show that morphological and vegetation characteristics in each zone also impact organic matter transformations through ephemeral streams.

Repeated minor flow events without an intervening higher-energy flushing flow may result in accumulation of fine silts and clays on channel and alluvial fan surfaces so that infiltration rates are impeded and overland flow becomes more frequent. Reduced infiltration leads to vegetation changes (woody shrubs at the expense of grasses) that reduce surface roughness and further increase runoff (Bull, 1997). This positive feedback can occur during prolonged drought on active (unincised) alluvial fans, increasing susceptibility to destructive incision when more powerful flows occur, or it can result from channel incision that cuts alluvial soils off from regenerative flushing flows.

Results from our analyses of alluvial soils of terraces and active alluvial fans show distinct differences in physical properties that suggest disturbance driven, flood-

pulse dynamics on active alluvial fans and stable, relatively tight nutrient cycles on terraces. These observations have important implications for understanding rejuvenating processes that drive long-term traditional runoff agriculture as well as other vital ecological and hydrological functions of small-scale, tributary alluvial fans. Chapter four explores alluvial soils in more detail.

Chapter 4: Soil morphology and N dynamics on flooded and incised alluvial fans

INTRODUCTION

Soil degradation is a worldwide issue of increasing concern (National Research Council, 1993), especially in semiarid regions vulnerable to desertification (Dregne, 1983; Le Houerou, 1996). Degradation often results when soil-forming processes are disrupted to destroy attributes developed over long periods, especially those associated with stored or protected organic matter (humus). Such disruptions result in temporary pulses of nutrient availability followed by long-term decline. Drainage of moist soils, for instance, accelerates mineralization and loss of organic matter accumulated in anoxic environments. Annual tillage also accelerates mineralization, temporarily increasing nutrient availability that are then harvested with crops rather than returned to the soil (Davidson and Ackerman, 1993; Schimel, 1986). Where flooding is a driving force in soil development, exclusion of those processes leads to degradation of properties that make alluvial soils some of the most productive (Hirst and Ibrahim, 1996; Hughes, 1994).

In arid and semiarid regions, depositional reaches of ephemeral streams are some of the most productive and diverse landscape positions, but are degraded when stream courses incise to become continuous channels. Alteration of natural flow regimes is blamed for environmental degradation including exotic species invasions (Stromberg, 1998), vegetation shifts that trigger desertification feedback processes (Bull, 1997), and changes to large scale river morphology that destroy critical fish and wildlife habitat (Poff et al., 1997). Occasional flooding, where alluvial landforms are hydrologically

connected to channels, creates ecological perturbation as it deposits fresh sediments and organic debris that drive active nutrient cycles. This alluvial fan version of the "flood pulse concept" (Junk et al., 1989) is not well understood, even though ephemeral streams systems comprise a major portion of the world's water resources (Davies et al., 1994).

The fertility and water absorbing capacity of alluvial deposits are recognized and valued in the culture of the Zuni Indians. Alluvial fans are important in traditional non-irrigated farming (Pawluk, 1995), as well as for forage and wildlife habitat. Historically, Zuni farmers worked to prevent downcutting and maintain depositional zones (Norton and Sandor, 1997), but the Zuni Tribe is facing growth issues that threaten traditional agricultural areas. Channelization and levying for flood prevention often accompany residential development and result in permanent drought and soil degradation for affected areas. Improved understanding of the value of linked fluvial and nutrient-cycling processes could aid land use decision-making at Zuni and in other semiarid environments.

Arid and semiarid lands drained by ephemeral streams cover a large and growing portion of the world (Dregne, 1983). Their ecological variability and unpredictability is often of a scale similar to that foretold by models of global climate change. The study of arid lands sheds insight on the types of extreme climatic variation that more stable ecosystems may to be tending toward. A great number of researchers are creating an excellent understanding of desertification processes and biogeochemical cycling in dry lands (Dregne, 1983; Le Houerou, 1996; Schlesinger et al., 1990). But so far, landscape relationships have been somewhat neglected, specifically the zones of increased productivity in aggradational reaches of desert washes.

Dry environments are characterized by short-lived pulses of productivity when moisture triggers nutrient dynamics in conditions ripe for rapid and complete mineralization. Combined with warm day-time temperatures and organic material broken down by severe desiccation (Sparling et al., 1995) and, in many dry regions, multiple freeze-thaw cycles (DeLuca et al., 1992), mineralization rates can deplete organic matter before soils dry out. In this "transient maxima" environment (Seastedt and Knapp, 1993), nutrients quickly take over for moisture as the limiting factor for plant growth (De Bruin et al., 1989). Irrigated soils in arid climates often become severely degraded because increased frequency of moist conditions drastically depletes already low soil organic matter levels, destroying beneficial soil properties associated with humus (Dregne, 1983).

Alluvial soils that are hydrologically connected to active ephemeral channels defy rapid depletion because influx of sediment and organic material renews soil productivity (Bull, 1990; Nabhan, 1979). Relatively little work describes changes in soil development and nutrient cycling processes under flooding and flood exclusion regimes. Jenny (1962) showed a rising N profile in Nile flood plain soils from yearly inputs of nutrient rich sediments. Workers in Bangladesh have shown that flood protection on farm fields near the Ganges River leads to depletion of soil nutrients (Hirst and Ibrahim, 1996).

The purpose of the work reported in this chapter was to describe soil forming processes and soil N dynamics attributable to flooding, and soil degradation attributable to exclusion from flooding. Ephemeral stream systems the scale of those described in this chapter are relatively easily maintained or restored. Better understanding of the value of intact alluvial systems may help land managers prioritize activities.

MATERIALS AND METHODS

Study Sites

I chose three active alluvial fans on the Zuni Reservation that had been recently flooded and have adjacent non-flooded terraces. The Paquin field lies approximately five km northwest of Zuni Pueblo at the mouth of an arroyo. The watershed covers about 179 ha with the upper part dominated by sandstone escarpments of the Zuni and Chinle formations and the lower part by sandy alluvium and eolian materials. The fan plot of the paired site lies just below the mouth of a shallow ephemeral channel in the north end of a field planted to corn each year since 1997. Before that the field was fallow for an unspecified number of years. The terrace plot lies approximately 100m east of the fan plot on an older alluvial surface now excluded from flooding. The terrace plot is uncultivated and dominated by needle grass (*Stipa comata*).

The Lalio field lies approximately 20 km east of Zuni Pueblo in the Cheama Canyon watershed. The fan plot lies on fresh (1997) alluvial sediments below the mouth of an arroyo (Figure 4–1) that drains 36 ha. Upper reaches of the watershed are dominated by pinyon-juniper (*Pinus edulis-Juniperus* spp.) woodlands underlain by Chinle and Zuni sandstones while big sagebrush (*Artemisia tridentata*)-blue grama (*Bouteloua gracilis*) grasslands cover sandy alluvium in the lower reaches. The fan plot lies near the edge of a hand-cultivated cornfield farmed by Ed Lalio and family each year since 1997. The field was fallow for many years before that. The terrace plot lies within the fenced field suggesting that it may have been cultivated some time ago. The plot is on an alluvial terrace where arroyo incision about 1.5m deep has excluded the western

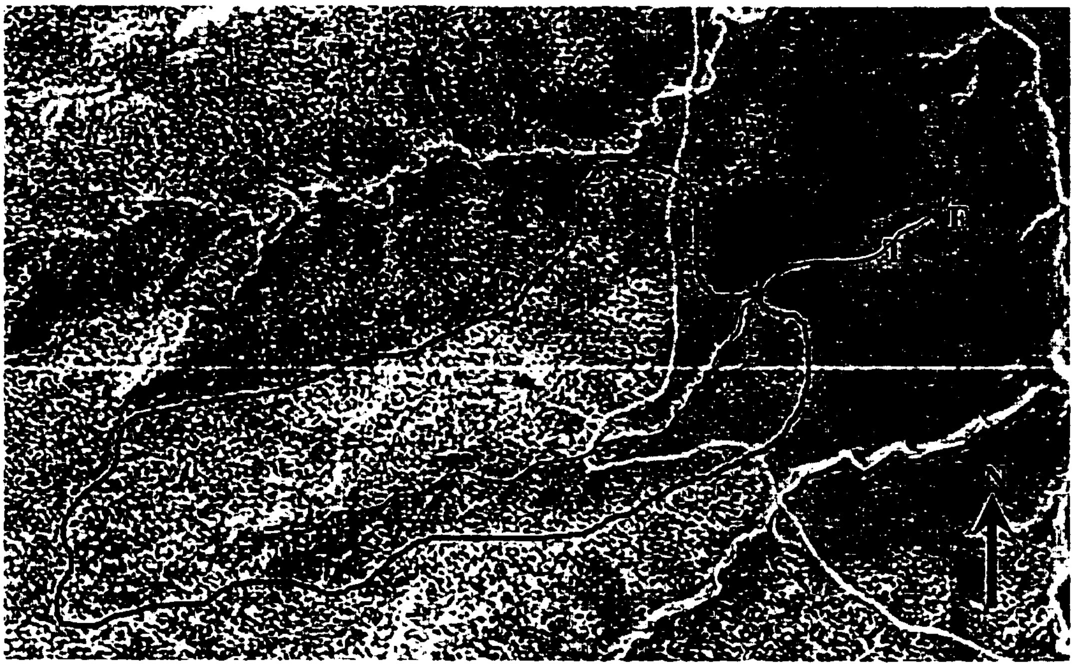

Figure 4–1. Lalio study site as an example of plot location. Each of the three study sites lie in a similar setting. F = fan plot, T = terrace plot. Scale is approximately 1:24,000. Dark line indicates watershed boundary; dashed line is approximate thalweg of arroyo channel.

portion of the field from flooding. Vegetation is dominated by blue grama, needle grass, and rabbitbrush (*Chrysothamnus nauseosus*).

The Sanchez field drains approximately 67 ha about 1km southwest of Pescado, near the eastern edge of the reservation. Interbedded shales and sandstones of the Gallup Sandstone formation underlie the upper reaches of the Sanchez watershed. Vegetation is dominated by pinyon-juniper woodlands with ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) on the upper slopes and by big sagebrush-blue grama grasslands on valley floor alluvial terraces. The fan plot lies in a broad swale that forms the flow path of ephemeral floods and the terrace plot lies at a slightly higher elevation that receives sheet flow from side slopes adjacent to the field but not from ephemeral stream flows. The Sanchez site is geomorphically farther down gradient that

the Paquin and Lalio sites. It lies well below the zone were sand and most coarse organic debris is deposited. Both Sanchez plots lie in a cultivated field, parts of which have been farmed intermittently with corn, wheat, and rye since at least 1991. The fan plot was in the edge of a corn section during the first year and fallow the second. The terrace plot was fallow both years.

Field and Laboratory Procedures

An *in-situ* field incubation study based on methods described by Raison et al. (1987) was carried out on two treatments (fan and terrace) for each study. Four replications of six cores (5cm X 40cm PVC pipe) were driven flush with the soil surface (Figure 4–2). Cores were spaced 1m apart and rows were laid out perpendicular to slope to stratify for distance along the alluvial gradient. One core was removed from each row after each incubation period, beginning August 6, 1998, and ending September 6, 1999.

A	4	3	5	2	6	1
B	5	1	4	2	3	6
C	3	5	1	6	2	4
D	6	2	5	1	3	4

Figure 4–2. Example plot layout for in-situ incubation study. Rows A-D run perpendicular to slope. One tube from each row was removed at the end of each sample period: 1 = 8/6/98; 2 = 9/29/98; 3 = 12/5/98; 4 = 3/16/99; 5 = 7/3/99; and 6 = 9/6/99.

Each PVC core was sealed with duct tape upon collection, transported on ice to the laboratory, and processed within three days. Soil cores were divided into 0-15 and 15-40 cm depths and subsamples were analyzed for gravimetric moisture content, nitrate-N concentration by nitration of salicylate (Yang et al., 1998) and ammonium-N concentration using the Berthelot reaction (Willis et al., 1993), and microbial biomass by fumugation-extraction-ninhydrin-reactive N concentration as described by (Joergensen and Brookes, 1990) and modified by (DeLuca and Keeney, 1993). Remainder of the soil was air-dried. Potentially mineralizable N (PMN) was determined using the 14d anaerobic incubation method described by Hart et al. (1994) on air dry samples wetted to -0.01 MPa and pre-incubated to reduce rewetting effects.

Soil pits hand excavated to 150cm depth adjacent to each incubation plot were described and sampled by standard methods (Natural Resource Conservation Service, 1993). Total C and N concentration in fine-ground, air dried samples from horizons ≤ 40 cm depth were determined using a Fissions EA1100 dry combustion CNSHO analyzer (Fissions Inst., Inc., Milan, Italy).

Plant production was determined by clipping three 1m^2 plots inside the incubation plots. Vegetation from each plot was air dried at 60°C, and weighed. Dominant species in each plot were identified.

RESULTS AND DISCUSSION

Flooding at the fan sites enhanced indicators of soil productivity while prolonged exclusion from flooding degraded soils of the terrace sites relative to flooded counterparts, though in different ways at each site. Differences between the fan and terrace soils include long-term changes to soil morphology and organic matter content,

and short-term effects on nutrient-cycling. Climatic data from Zuni Pueblo indicate that the study period was wetter and warmer than normal (Table 4–1), but within the +/- 26 percent standard deviation for precipitation (Western Regional Climate Center, 2000a).

Table 4–1. Study period compared to long-term precipitation and temperature (based on daily and long-term monthly data from Western Regional Climate Center, 2000).

	Precipitation			Mean Daily Temperature					
Date	Study Period	1949-2000 Mean	% of Mean	Study Period		1949-2000 Mean		% of Mean	
				Max.	*Min.*	*Max.*	*Min.*	*Max.*	*Min.*
	mm		%	°C				%	
Jul-98	1	51	*	31	13	31	12	*	*
Aug-98	46	57	*82*	32	13	30	12	*107*	*107*
Sep-98	36	31	*114*	29	10	27	8	*111*	*120*
Oct-98	82	30	*272*	21	2	21	2	*102*	*109*
Nov-98	38	20	*190*	15	-3	14	-4	*113*	*77*
Dec-98	17	21	*82*	12	-8	9	-8	*134*	*95*
Jan-99	1	22	*6*	13	-9	8	-9	*156*	*108*
Feb-99	3	18	*14*	15	-8	10	-6	*145*	*127*
Mar-99	5	24	*23*	19	-4	14	-4	*137*	*106*
Apr-99	14	15	*90*	18	-2	19	-1	*96*	*286*
May-99	18	12	*148*	24	4	24	3	*104*	*102*
Jun-99	11	10	*103*	30	7	29	8	*102*	*86*
Jul-99	78	51	*155*	31	13	31	12	*98*	*109*
Aug-99	91	57	*161*	30	12	30	12	*100*	*102*
Sep-99	27	31	*	28	10	27	8	*	*
Total**	440	368	*120*	289	25	264	25	*109*	*101*

* Study period included only part of month.

** Total and mean for 13 months from Aug-98 to Aug-99.

Long-Term Effects: Soil Morphology and Organic Matter Content

Soil profile analyses show influences of fluvial processes in each of the six soils but, to varying degree, the fan soils each have darker colors, coarser texture, and more organic matter in the terrace soils (Table 4–2).

Table 4–2. Total C and N from upper horizons. Based on soil profile samples from one soil pit at each site.

Site	Horizon	Depth	Texture	Total N	Total C	C:N
Paquin		*cm*		—*mg*	*kg^{-1}*—	
Fan	Ap/Oi	0-17	sandy loam	3686	86306	23
	BC1(om)	17-22	om masses	2643	65472	25
	BC1	17-26	sandy loam	510	13276	26
	2BC2	26-49	sandy loam	700	9039	13
	2BC2(om)	40-42	om laminae	1964	42275	22
Terrace	A	0-11	fine sand	300*	7383	25
	C1	11-25	fine sand	300*	6954	23
	C2	25-37	loamy sand	700*	7100*	10
	C3	37-60	loamy sand	300*	6123	20
Lalio						
Fan	C	0-12	loamy sand	700*	7100	10
	C2	12-22	sandy loam	847	16485	19
	2Ab	22-50	sandy loam	300*	6643	22
Terrace	A	0-8	loamy sand	700*	8168	12
	Bw	8-31	loamy sand	300*	6323	21
	2C1	31-120	gravel, sand	700*	7100*	10
Sanchez						
Fan	Ap	0-4	loam	763	9332	12
	Bt	4-26	clay loam	756	9129	12
	2BC	26-42	fine sand	1272	23057$^{\alpha}$	18
Terrace	Ap	0-7	clay loam	1352	16273	12
	Bt	7-35	clay	1133	13808	12
	Bt2	35-60	clay	591	8325	14

* Near or below detection limit; estimated as less than value presented.
** Percent change in 0-40 cm N and C with exclusion of flooding.
$^{\alpha}$ Charcoal fragments present

The Paquin fan soil is especially rich in organic matter, with fresh and slightly decomposed pinyon (*Pinus edulis*) and juniper (*Juniperus* spp.) debris in surface horizons and more decomposed material down to 97 cm depth (Table 4–3). This is reflected in high concentrations of total N and C, as well as the highest C to N ratio among the three study sites (Table 4–2). The upper 40 cm of the Paquin fan soil has nearly five times more total N and over six times more total C than the terrace soil (Table 4–4), reflecting influx of waterborne organic matter.

Table 4–3. Paquin paired soil profile descriptions.

Paquin Terrace: Sandy, mixed (calcareous), mesic, Aridic Ustipsamments
Parent material: sandy alluvium and eolian material derived from Zuni Sandstone
Excavated and described by Jay Norton, Troy Lucio, and Wilmer Quandelacy, September 15, 1998.

A	0-11cm	Yellowish red (5YR 5/6) loamy fine sand, yellowish red (5YR 4/6) moist; massive; soft, very friable, non-sticky, non-plastic; many fine and common medium roots; strongly effervescent; abrupt wavy boundary.
C1	11-25	Yellowish red (5YR 5/6) loamy fine sand, yellowish red (5YR 4/6) moist; fine cross-bedded laminae; soft, very friable, non-sticky, non-plastic, common fine roots; strongly effervescent; abrupt wavy boundary.
C2	25-37	Yellowish red (5YR 5/6) loamy fine sand, yellowish red (5YR 4/6) moist; massive; soft, very friable, non-sticky, non-plastic; few fine roots; strongly effervescent; abrupt wavy boundary.
C3	37-60	Reddish yellow (5YR 6/6) loamy fine sand, yellowish red (5YR 5/6) moist; fine cross-bedded laminae; soft, very friable, non-sticky, non-plastic, common fine roots; strongly effervescent; abrupt wavy boundary.
C4	60-105	Reddish yellow (5YR 6/6) loamy fine sand, yellowish red (5YR 5/6) moist; massive; soft, very friable, non-sticky, non-plastic; few fine roots; strongly effervescent; abrupt wavy boundary.
C5	105-123	Yellowish red (5YR 5/6) loamy fine sand, yellowish red (5YR 4/6) moist; fine cross-bedded laminae; soft, very friable, non-sticky, non-plastic, common fine roots; strongly effervescent; abrupt wavy boundary.
2Btb	123-150+	Yellowish red (5YR 5/6) sandy loam, yellowish red (5YR 4/6) moist; weak, medium subangular blocks; slightly hard, very friable, slightly sticky, slightly plastic; few thin clay coatings; strongly effervescent.

Paquin Alluvial Fan: Coarse-loamy, mixed (calcareous), mesic, Aridic Ustifluvents
Parent material: sandy alluvium
Excavated and described by Jay Norton, Troy Lucio, and Wilmer Quandelacy, September 15, 1998.

Ap/Oi	10-17cm	Reddish brown (5YR 5/4) very fine sandy loam mixed with black slightly decomposed pine needles and juniper leaves, reddish brown (5YR 4/4) moist; weak medium to coarse subangular blocks; soft, very friable, non-sticky, non-plastic; few fine roots; moderately alkaline (pH 8.0); strongly effervescent; abrupt wavy boundary.
BC1	17-26	Laminated reddish brown (5YR 5/4) very fine sandy loam (18% clay) and yellowish red (5YR 4/6) silt (<15% clay) (silt laminae form ~40% of the horizon) with common fine distinct black (5YR 2.5/1) organic matter masses; weak fine subangular blocks breaking to single grains; soft, very friable, non-sticky, non-plastic; few fine roots; moderately alkaline (pH 8.0); strongly effervescent; clear wavy boundary.
2BC2	26-49	Yellowish red (5YR 4/6) fine sandy loam (15% clay) with loose loamy sand laminae making up about 40% of the horizon; few fine distinct masses and 2cm thick discontinuous lens of black (5YR 2.5/1) organic matter; weak fine subangular blocks breaking to single grains; soft, very friable, non-sticky, non-plastic; few fine roots; moderately alkaline (pH 8.0); strongly effervescent; clear wavy boundary.
3Abb	49-97	Laminated yellowish red (5YR 5/6) fine sandy loam and dark reddish brown (5YR 3/4) silt loam; thin wavy laminae and common fine distinct masses of black (5YR 2.5/1) organic matter; weak fine to medium subangular blocks; soft, very friable, non-sticky, non-plastic; few fine and medium roots; moderately alkaline (pH 8.0); strongly effervescent; abrupt wavy boundary.
3Btb	97-136	Yellowish red (5YR 4/6) loamy sand to sandy loam (15% clay); moderate medium subangular blocks and weak medium plates; few thin clay coatings and bridges between grains; common fine roots; mildly alkaline (pH 7.8); strongly effervescent; abrupt wavy boundary.
3C	136-150+	Yellowish red (5YR 5/6) loamy sand (<15% clay); weak subangular blocks breaking to single grains; soft, very friable, non-sticky, non-plastic; few fine roots; mildly alkaline (pH 7.8); strongly effervescent.

Note: Augered to from 150 to 300 cm depth: loamy sand with clayey stratum at 250 cm depth.

Table 4–4. Total C and N in upper 40 cm. Based on weighted average of values reported in Table 4-2.

Depth	Paquin Fan	Paquin Terrace	Δ	Lalio Fan	Lalio Terrace	Δ	Sanchez Fan	Sanchez Terrace	Δ
cm	—*g m^{-2}*—		*%*	—*g m^{-2}*—		*%*	—*g m^{-2}*—		*%*
Total N									
0-15	708	66	-90	175	123	-30	259	148	-43
15-40	541	203	-62	173	206	+19	358	392	+9
0-40	1249	269	-78	348	329	-5	618	540	-13
Total C									
0-15	16571	1592	-72	2154	1754	-19	3141	1791	-43
15-40	11425	2856	-75	3602	2409	-33	4449	6348	+43
0-40	27996	4448	-84	5757	4163	-28	7590	8139	+7

In the terrace pedon, fine cross-bedded laminae alternate with unlaminated beds of sandy sediments suggesting deposition from shifting flow regimes in an alluvial fan environment, but lack of organic matter suggests long-term loss of organic material in the flood-exclusion environment. Both the fan and terrace pedons show signs of long-term stability in their subsoils, with buried soil horizons (translocated clay) occurring at 97 cm in the fan soil and 123 cm in the terrace soil. This suggests that both were stable surfaces excluded from flooding at some time in the past, and that the channel now crossing the fan plot was located somewhere else.

In the Lalio fan pedon, two layers of cross-bedded loamy overwash lay atop a more developed buried soil (Table 4–5). The layers of fresh overwash are from two intense flood events in 1997 (personal communication, Quinton Lalio, Zuni Conservation Project, 1997). The top horizon (C, 0-12 cm) is pure loamy sand but the second (earlier) horizon (C2, 12-22 cm) has mixed decomposed organic matter and pinyon pine needles in fine black masses. This is reflected in the elevated total N and C concentrations in the C2 horizon (Table 4–2). This suggests that the first flood, which followed over a year of very

Table 4–5. Lalio paired soil profile descriptions.

Lalio Terrace: Sandy-skeletal, mixed (calcareous), mesic, Fluventic Ustochrepts
Parent material: sandy/gravelly alluvium
Excavated and described by Jay Norton, Troy Lucio, and Wilmer Quandelacy, September 17, 1998.

A	0-8	Yellowish red (5YR 5/6) loamy sand (10% clay), reddish brown (5YR 4/4) moist; weak fine subangular blocks breaking to single grains; soft, very friable; many fine roots; strongly effervescent; clear smooth boundry.
Bw	8-31	Yellowish red (5YR 5/6) gravelly loamy sand (10% clay, 20% gravel, 5% cobbles), yellowish red (5YR 4/6) moist; moderate fine to medium subangular blocks; soft, very friable; many fine roots; strongly effervescent; clear wavy boundary.
2C1	31-120	Interbedded gravel and loamy sand:
2C2	31-50	Yellowish red (5YR 5/6) loamy sand (10% clay), yellowish red (5YR 4/6) moist; weak fine to medium subangular blocks; soft, very friable; common fine roots; effervescent; abrupt wavy boundary.
2C3	50-54	Angular to subangular mixed sandstone gravel; abrupt wavy boundary.
2C4	54-84	Yellowish red loamy sand (as 31-50cm).
2C5	84-120	Gravel (as 50-54cm).
3Ab	120-131	Dark brown (7.5YR 4/4) loamy fine sand (12% clay); moderate fine to medium subangular blocks; soft, very friable; very few fine roots; common fine tubular pores; audible effervescence; gradual smooth boundary.
3Btb	131-148	Dark brown (7.5YR 4/4) loam (17% clay); weak medium prisms breaking to moderate fine subangular blocks; slightly hard, friable; common moderately thick clay coatings on ped faces; few fine roots; few fine tubular pores; no effervescence; gradual smooth boundary.
3Btkb	148-161+	Dark reddish brown (5YR 3/4) loam (17% clay); moderate medium subangular blocks; slightly hard, friable; common moderately thick clay coatings on ped faces; few fine roots; few fine tubular pores; violently effervescent.

Lalio Field Alluvial Fan: Coarse-loamy, mixed (calcareous), mesic, Aridic Ustifluvents
Parent material: sandy alluvium derived from Chinle Sandstone
Excavated and described by Jay Norton, Troy Lucio, and Wilmer Quandelacy, September 17, 1998.

C	0-12cm	Yellowish red (5YR 5/6) cross-bedded loamy sand (<10% clay), yellowish red (5YR 4/6) moist; weak medium plates/laminae; soft, friable, non-sticky, non-plastic; common fine roots; strongly effervescent; abrupt smooth boundary.
C2	12-22	Yellowish red (5YR 4/6) sandy loam (15% clay), reddish brown (5YR 4/4) moist; many fine distinct Oi masses some pine needles; weak medium plates/laminae breaking to weak medium subangular blocks; soft, friable, non-sticky, non-plastic; few thin coatings on sand grains associated with Oi masses; common fine and medium roots; strongly effervescent, few fine hard masses of Cate; clear smooth boundary.
2Ab	22-50	Mottled reddish brown (5YR 4/5) and dark reddish brown (5YR 3.5/4) loamy sand and sandy loam (<15% clay); common fine faint organic matter masses; weak medium subangular blocks; slightly hard, friable, non-sticky, non-plastic; few thin coatings on sand grains; common fine roots; common tubular pores; strongly effervescent, common fine Cate masses and filaments; clear smooth boundary.
3ABb	50-55	Dark reddish brown (5YR 3/4) silt loam (18% clay); weak fine subangular blocks; slightly hard, friable, non-sticky, non-plastic; common fine roots; common tubular pores; strongly effervescent; clear smooth boundary.
3BCb	55-77	Reddish brown (5YR 4/5) fine sandy loam (10% clay); weak fine subangular blocks; slightly hard, friable, non-sticky, non-plastic; common fine roots; effervescent; clear smooth boundary.
4BCb2	77-92	Reddish brown (5YR 4/4) silt loam (18% clay); weak fine subangular blocks; slightly hard, friable, non-sticky, non-plastic; common fine roots; effervescent; clear smooth boundary.
5Btkb	92-119	Reddish brown (5YR 4/4) sandy loam (15-18% clay); moderate fine subangular blocky; slightly hard, friable; few thin clay coatings; few fine roots; few fine to medium tubular pores; violently effervescent, common very fine Cate masses; gradual smooth boundary.
5Btkb2	119-150+	Dark reddish brown (5YR 3/4) sandy loam (15% clay); moderate fine subangular blocks; slightly hard, friable; common thin clay coatings; few fine roots; few fine to medium tubular pores; violently effervescent, common fine to medium Cate masses and filaments.

dry weather, may have washed accumulated forest litter from watershed hillslopes before the second flood occurred about one week later. Both Lalio soils have multiple flood deposits over better-developed buried horizons. The Bw horizon near the surface of the terrace soil suggests that the underlying alluvial deposits (2C horizons) are relatively old. The Lalio soils both have illuvial Cate and clay accumulations beginning about 148 cm in the terrace soil and 92 cm in the fan soil, or 70 cm without the recent overwash, suggesting relative stability to provide time for translocation. The greater depth of illuvial materials in the terrace soil, even though the fan soil probably receives more moisture and alluvial thickening of surface layers, suggests longer-term stability, though strata of gravel and cobbles in the terrace soil may accelerate translocation.

Both Sanchez pedons are classified as Aridic Haplustalfs but the terrace soil has much finer texture than the fan soil throughout most of the pedon, particularly the upper 60 cm (Table 4–6). Color and depth to buried soils are the most striking differences, other than texture, between the two Sanchez soils. Most horizons of the fan soil are darker than those of the terrace soil, particularly in the lower, buried horizons, and the terrace soils were extremely hard compared to the fan soils. Soil degradation is not evident in organic matter contents, however (Table 4–2); nor is there differences in soil moisture content. This suggests that clayey materials accumulated in the absence of flooding may offset advantages of organic matter. The terrace soil is below a slope consisting of clayey soils formed in Cretaceous shale or mudstone. Fine sediments washed from this hillside accumulate on the alluvial valley floor because exclusion from flooding deprives the site of flushing flows. The result is a clayey soil with similar moisture and nutrient content to the fan soil, but, probably, less available moisture and

nutrients. A characteristic of clay

Table 4–6. Sanchez paired soil profile descriptions.

Sanchez Terrace: Clayey over loamy, mixed, mesic, Aridic Haplustalfs
Parent material: alluvium derived from interbedded sandstone and shale of the Gallup Sandstone.
Excavated and described by Jay Norton, Troy Lucio, and Wilmer Quandelacy, September 30, 1998.

Ap	0-7cm	Pale brown (10YR 6/3) clay loam (32% clay, 5% gravel), brown (10YR 4/3) moist; weak moderate plates; very hard, firm, sticky, plastic; common fine roots; many moderate horizontal cracks; clear smooth boundary.
Bt	7-35	Dark brown (10YR 4/3) clay (60% clay, 5% gravel); moderate medium prisms breaking to moderate medium angular blocks; very hard, very firm, sticky, plastic; common moderately thick clay coatings on ped faces; few fine roots; common medium vertical cracks; gradual smooth boundary.
Bt2	35-60	Dark brown (10YR 4/3) clay (45% clay, 5% gravel); moderate medium subangular blocks; very hard, firm, very sticky, very plastic; common moderately thick clay coatings on ped faces; very few fine roots; few fine cracks; abrupt smooth boundary.
2Ck	60-102	Yellowish brown (10YR 5/5) sandy loam (10% clay, 8% gravel, 5% cobbles); massive; hard, friable, slightly sticky, slightly plastic; common fine roots; common vertical cracks; strongly effervescent (violent adjacent to coarse fragments); clear wavy boundary.
3Btkb	102-120	Yellowish brown (10YR 5/4) loam; moderate fine to medium subangular blocks; very hard, firm, slightly sticky, slightly plastic; common thin clay coatings on ped faces; common fine roots; strongly effervescent; clear wavy boundary.
3Btkb2	120-134+	Dark yellowish brown (10YR 4/4) clay loam (23% clay); weak subangular blocks to massive; very hard, firm, sticky, plastic; common thin clay coatings on ped faces; few fine roots; effervescent.

Sanchez Alluvial Fan: Fine-loamy, mixed, mesic, Aridic Haplustalfs
Parent material: alluvium derived from interbedded sandstone and shale of the Gallup Sandstone.
Excavated and described by Jay Norton, Troy Lucio, and Wilmer Quandelacy, September 30, 1998.

Ap	0-4cm	Brown (10YR 5/3) loam(15% clay, 5% gravel), brown/dark brown (10YR 4/3) moist; weak fine subangular blocks; slightly hard, firm, non-sticky, non-plastic; common fine and medium roots; common coarse cracks; clear wavy boundary.
Bt1	4-14	Dark brown (10YR 3/3) clay loam (30% clay, 5% gravel) ; moderate fine subangular blocks; hard, firm, sticky, plastic; common moderately thick clay coatings; few fine and common medium roots; common vertical cracks with brown/dark brown (10YR 4/3) silt coatings; clear wavy boundary.
Bt2	14-26	Brown/dark brown (10YR 4/3) clay loam (30% clay, 5% gravel); moderate to strong medium prisms; slightly hard, firm, sticky, plastic; common moderately thick clay coatings; common fine and medium roots; common vertical cracks; clear wavy boundary.
2BC	26-42	Cross-bedded laminae of yellowish brown (10YR 5/5) fine sand and dark yellowish brown (10YR 4/4) silt and clay with common fine charcoal fragments; moderate fine to medium subangular blocks and fine medium plates; slightly hard, firm, sticky, plastic; few thin clay coatings; common fine and few medium roots; clear wavy boundary.
3Btb	42-69	Brown/dark brown (10YR 4/3) clay loam (40% clay); strong medium subangular blocks; hard, firm, sticky, plastic; common moderately thick clay coatings on ped faces; common vertical cracks with dark yellowish brown (10YR 4/5) silt coatings; gradual smooth boundary.
3Btkb	69-102	Dark yellowish brown (10YR 4/4) sandy loam (18% clay, 10% gravel); moderate medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; common thin clay coatings on ped faces; few fine roots; strongly effervescent; clear smooth boundary
4BC	102-109	Brown/dark brown (10YR 4/3) gravelly sandy clay loam (20% clay. 15% fine gravel); few fine charcoal fragments; moderate fine subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; very few fine roots; slightly effervescent; clear smooth boundary.
5C1	109-125	Dark yellowish brown (10YR 4/6) gravelly loamy sand (30% gravel); single grain; loose; very few fine roots; audible effervescence; clear smooth boundary.
6C2	125-150+	Interbedded dark brown (10YR 4/3) silt loam and dark yellowish brown (10YR 4/6) loamy sand; weak fine subangular blocks and moderate fine plates; soft, very friable; very few fine roots; audible effervescence in sandy laminae, strong effervescence and few fine Cate filaments in silty laminae.

soils is high water-holding capacity but relatively low water availability because much is held in micro pores. Similarly, clayey soils hold nutrients associated with organic matter and may be too hard and massive for plants to exploit. Sandy and loamy horizons beginning at 60 cm depth suggest floodwaters from the main ephemeral stream course previously inundated the area.

All three of the terrace pedons show degradation resulting from long-term exclusion from flooding when compared to the fan soils. At the Paquin and Lalio sites both fan and terrace soils consist of stacked alluvial strata but the fan soils have lenses and masses of organic material transported from wooded watershed slopes while the terrace soils are mostly devoid of organic matter. Organic matter contents are similar among the two Sanchez soils but, with exclusion of larger floods, the terrace soil is dominated by clayey sediments from low energy sheetwash.

Short-Term Effects: Soil Moisture and N dynamics

Results from the *in-situ* incubation study suggest pulses of nitrification during incubation periods that ended on 12/5/98 and 7/3/99 (Figure 4–3, Figure 4–4, and Figure 4–5). The nitrate-N peaks in the Paquin fan soils are the most striking, with marked differences between the fan and terrace soils. The 12/5/98 nitrate-N peak corresponds with soil moisture content peaks at all three sites, as rewetting of dry soils drives mineralization (Van Gestel et al., 1993). The highest peak occurs in the 15-40 cm depth sample suggesting excess nitrate and moisture leach through the pedon. Moisture content is low on 7/3/99, however, and neither nitrate-N pulse corresponds with peaks in ammonium-N or microbial biomass C, both of which remain relatively low and steady.

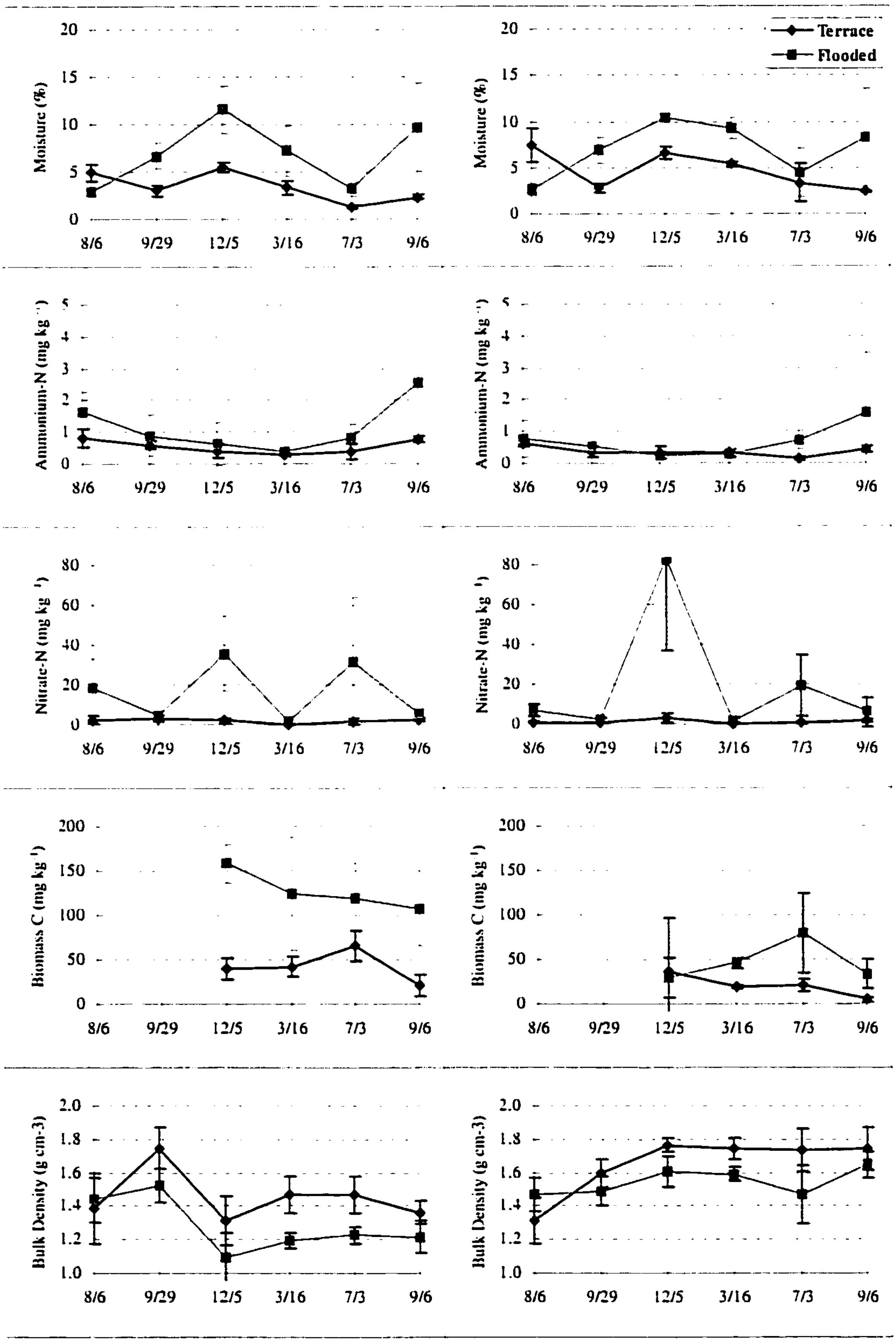

Figure 4–3. Results of *in-situ* incubation, Paquin site. Values for 0-15 cm depth samples is on the left, 15-40 cm on the right.

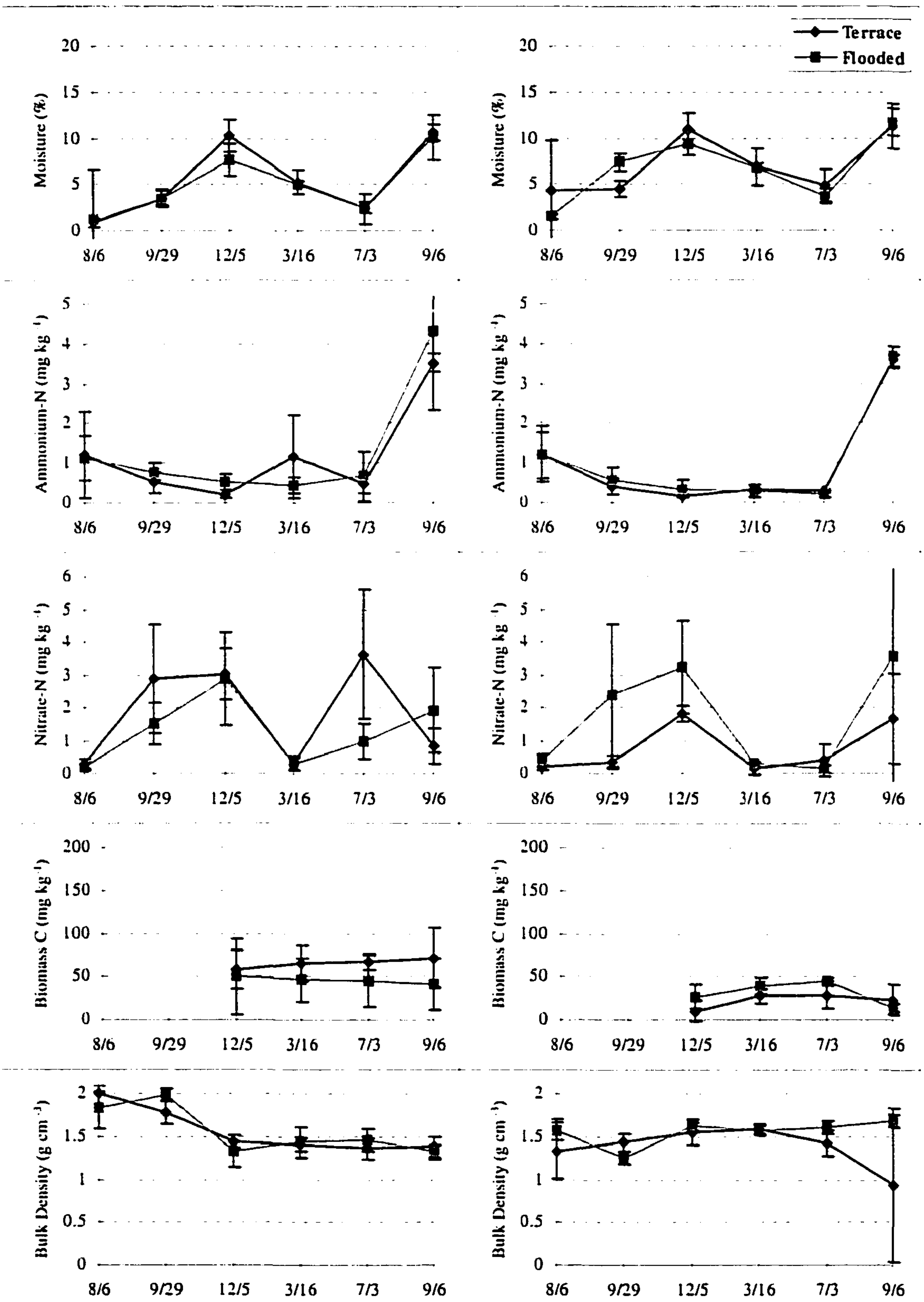

Figure 4–4. Results of *in-situ* incubation, Lalio site. Values for 0-15 cm depth samples is on the left, 15-40 cm on the right.

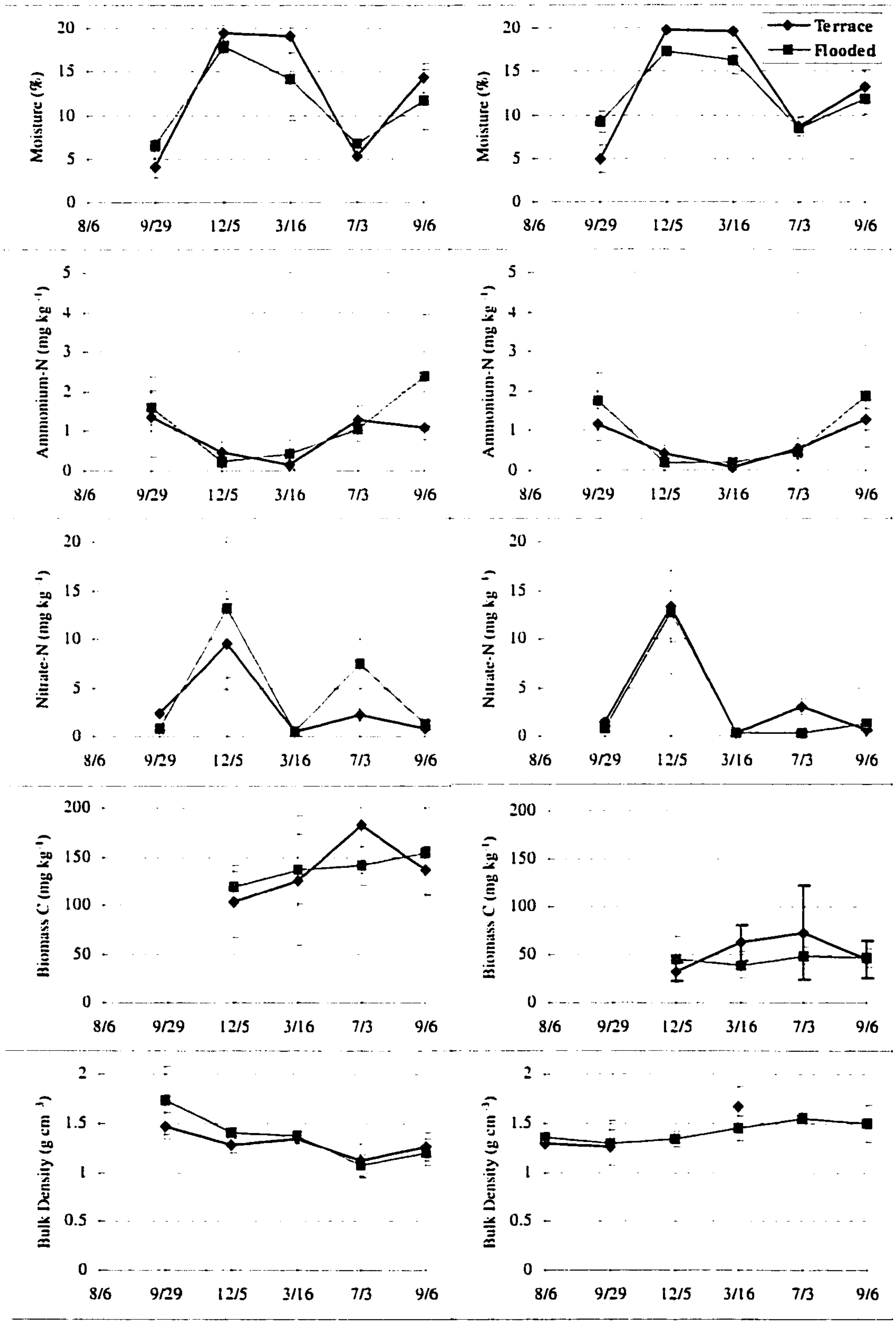

Figure 4–5. Results of *in-situ* incubation, Sanchez site. Values for 0-15 cm depth samples is on the left, 15-40 cm on the right.

The low microbial biomass levels suggest that pulses of nitrification may be driven more by mineralization of dead plant residues than turnover of microbial biomass. Microbial biomass is thought to be an important driver of N mineralization after drying and rewetting (Sparling et al., 1995) and freeze-thaw cycles (DeLuca et al., 1992) in most soils. Alternatively, microbial populations may be so volatile that fluctuations occurred between sampling dates and were missed by the analyses. Cui and Caldwell (1997) found that microbial populations responded rapidly to rewetting of dry soils in semiarid Utah grasslands. They recorded large increases in soil nitrate with wetting after a long dry period, but levels decreased back to control concentrations within a week.

Ammonium-N concentrations are lower and do not fluctuate as strikingly as nitrate-N, even though ammonification is the first step and nitrification the end product of mineralization (Paul and Clark, 1996). This suggests that pulses of ammonification were followed rapidly by nitrification, as reflected in the nitrate-N pulses.

Climatic conditions (Figure 4–6) suggest that the 12/5/98 pulse was driven by combined effects of flooding, wet weather, and freeze-thaw cycles. Heavy rainfall (4.9 cm) on 10/26 was followed by cold nighttime temperatures (<-20°C) and two lighter, but substantial rains in November (2.2 cm on 11/9 and 1.1 cm on 11/30). Then, just before the 12/5/98 sampling, day-time temperatures climbed to over +20°C. On 12/5/98 I noted flood debris deposited since the previous sampling, probably during the 10/26 storm. These relationships suggest that repeated wet-dry and freeze-thaw cycles in November, and warm temperatures just before the sampling date drove mineralization of fresh flood deposits to create elevated nitrate-N concentrations on 12/5/98.

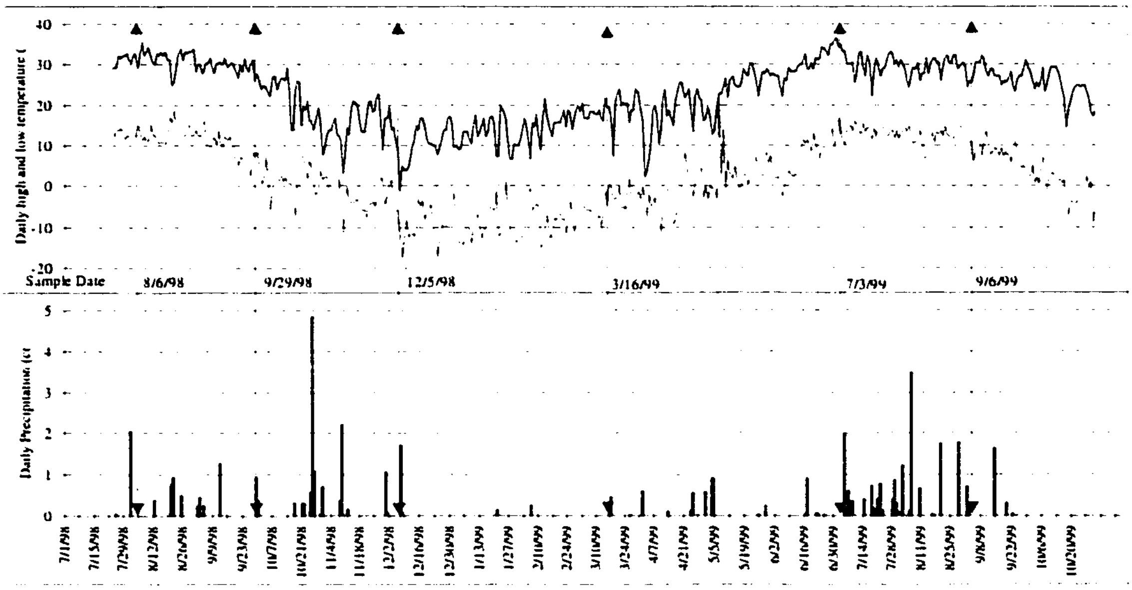

Figure 4–6. Daily high and low temperatures and daily precipitation during the study period. Source: Western Regional Climate Center, Desert Research Institute, Reno, Nevada. Arrows indicate sampling dates.

Rewetting of dry soils generates a pulse of mineralization caused by nutrient-release from cells killed during drying and from physical breakdown that increases accessibility of organic matter to microorganisms (Sarig and Steinberger, 1993). Many researchers also report that freeze-thaw cycles stimulate pulses of net N mineralization (DeLuca et al., 1992), denitrification, (Christensen and Christensen, 1991), or immobilization depending on initial moisture, C availability, and the nature of the freeze event(s) (Honeycutt, 1995; Vaz et al., 1994).

Climatic data prior to the 7/3/99 nitrate pulse suggests a different scenario. This sample date was preceded by a very dry spring, but a 9 mm rain on June 17 was followed by the hottest daytime temperatures of the year (nearly 40°C). The June 17 rain probably triggered rapid mineralization in the previously desiccated soils, but intense drying shortly afterward may have arrested denitrification and immobilization, leaving relatively high nitrate-N concentrations and low soil moisture content on 7/3/99. Sarig and

Steinberger (1993), working with warm desert soils of the Negev (Israel), found flushes of biological activity out of proportion to the size of precipitation events and suggest that minor showers or even dew formation can cause large increases in microbial populations. As pointed out by Cui and Caldwell (1997), however, this flush of activity can be very short-lived with the return of hot and dry conditions. This situation would leave a ready source of mineral and mineralizable N for rapid uptake by plants and microbes with the next rain shower. This is also suggested, though inconclusively, by elevated PMN concentrations in some of the 9/6/99 soils relative to the previous sampling (Figure 4–7).

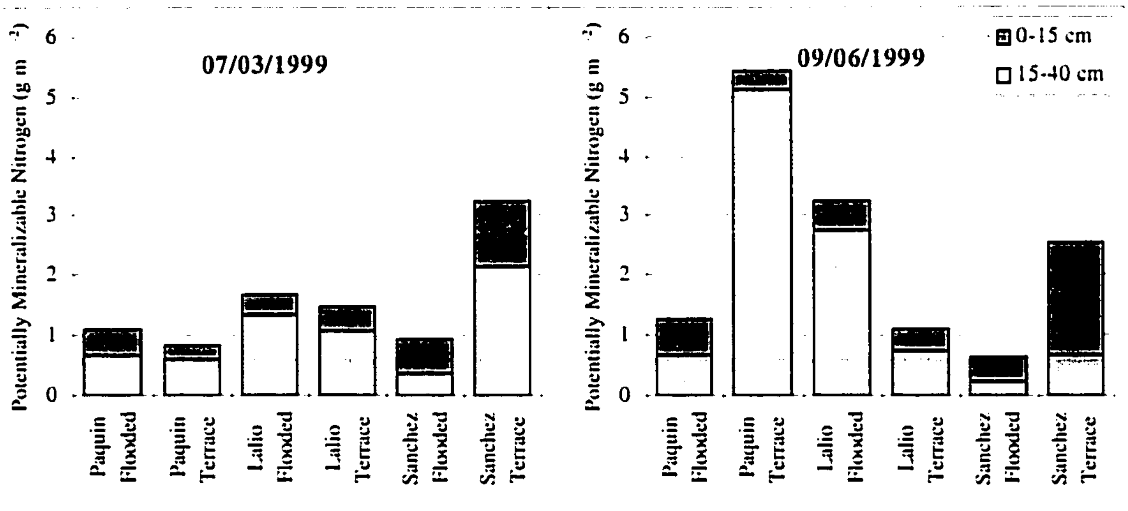

Figure 4–7. Potentially mineralizable N for two sample dates.

The very low nitrate-N concentrations between the recorded pulses, without increases in microbial biomass C, suggests that denitrification played an important role in the incubation tubes as well. Nitrate-N concentrations at the Paquin site are near zero on 9/29/98, 3/16/99, and 9/6/99 (Figure 4–3). Each of these dates corresponds with relatively moist soils and follows prolonged moist periods or repeated wet-dry cycles. The 9/29/98 sampling followed over six weeks of very warm weather with several minor,

non-flood generating rainfall events. This combination, without further deposition or physical disturbance, may have driven mineralization to completion in the incubation tubes. The 3/16/99 sampling followed a very dry winter, but cool temperatures and the sandy surface probably maintained enough moisture from the wet fall to drive denitrification. The 9/6/99 sampling followed over two months of very warm and unusually moist weather which combined with the high nitrate-N concentrations recorded on 7/3/99 to generate a dense and tall canopy of sunflower. Rainfall on August 6 generated minor flooding and deposition of sediment and organic debris on the plot. Though the tubes prevented plant uptake, the canopy maintained moist conditions that may have driven denitrification during warm summer months.

Peterjohn (1991) suggests that denitrification rates are high in desert soils, accounting for around 70 percent of N inputs from all sources. He shows that denitrification in wet desert soils is limited by C availability. Relatively high organic matter concentrations and high C:N ratios in the alluvial soils I studied suggest the possibility of substantial N losses to denitrification. This may be evident in the results of the last sampling date, 9/6/99

Table 4–7 shows that fan soils of the Paquin site, with the most recent flood deposits, have many attributes that suggest greater productivity than adjacent terrace soils. All the parameters show significant degradation with exclusion of flooding. Table 4–8 shows that vegetation productivity at the Paquin site was drastically altered by exclusion of flooding as well.

Table 4–7. Change in soil moisture and nutrients attributable to absence of flooding, 0-40cm.

Site	Time	Fan	Terrace	Δ*	Fan	Terrace	Δ*	Fan	Terrace	Δ*	Fan	Terrace	Δ*	Fan	Terrace	Δ*
		Moisture			Bulk Density			Nitrate-N			Ammonium-N			Biomass C**		
		—%—		%	—g cm^{-3}—		%	—g m^{-2}—		%	—g m^{-2}—		%	—g m^{-2}—		%
Paquin	8/6/98	2.76	6.51	**136**	1.46	1.34	-8	6.09	0.86	**-86**	0.61	0.29	**-53**			
	9/29/98	6.79	2.88	**-58**	1.50	1.65	**10**	1.78	1.20	-32	0.39	0.24	-39			
	12/5/98	10.85	6.18	***-43***	1.41	1.60	*13*	38.29	1.70	**-96**	0.20	0.17	-15	37.72	16.96	**-55**
	3/16/99	8.52	4.61	***-46***	1.44	1.64	***14***	1.04	0.05	**-95**	0.19	0.15	-23	39.82	14.08	***-65***
	7/3/99	4.01	2.61	-35	1.38	1.63	**19**	12.13	0.47	*-96*	0.40	0.13	***-69***	49.44	19.64	***-60***
	9/6/99	8.77	2.36	**-73**	1.48	1.60	*8*	3.34	1.11	-67	1.11	0.27	-75	33.04	5.34	***-84***
Lalio	8/6/98	1.39	3.00	115	1.68	1.59	-5	0.21	0.15	-27	0.80	0.62	-23			
	9/29/98	5.95	4.17	***-30***	1.53	1.56	2	1.20	0.91	*-24*	0.40	0.23	*-43*			
	12/5/98	8.75	10.67	22	1.51	1.51	0	1.84	1.35	**-26**	0.24	0.09	**-63**	19.85	14.87	-25
	3/16/99	6.16	6.35	3	1.52	1.52	0	0.17	0.12	-30	0.20	0.32	57	24.88	20.37	-18
	7/3/99	3.23	3.98	23	1.55	1.39	**-10**	0.27	0.88	*232*	0.22	0.16	-26	27.58	19.50	*-29*
	9/6/99	11.14	11.07	-1	1.55	1.10	-29	1.89	0.34	-82	2.40	1.24	**-48**	13.84	18.04	30
Sanchez[1]	8/6/98															
	9/29/98	8.18	4.56	***-44***	1.46	1.33	**-9**	0.36	0.79	***122***	0.73	0.53	-27			
	12/5/98	17.50	19.68	*13*	1.36	1.51	**11**	6.96	7.30	*5*	0.11	0.20	*82*	39.64	32.92	-17
	3/16/99	15.43	19.47	**26**	1.42	1.54	**9**	0.19	0.19	1	0.16	0.06	**-66**	41.87	48.00	15
	7/3/99	7.85	7.41	-5	1.37	1.46	7	1.82	2.06	13	0.20	0.20	-2	38.76	43.74	13
	9/6/99	11.86	13.67	15	1.38	1.51	*9*	0.23	1.34	***476***	0.27	0.17	-38	46.89	43.37	-8

* t-test results for statistical significance: Italics: P<0.1; Bold: P<0.05; Bold italics: P<0.01.

** Analysis began with third sample collection.

1. Sampling began with second collection.

Table 4–8. Air-dry vegetation yield and percent difference, fan to terrace.

	Plant Biomass		
	Fan	Terrace	Δ*
	—g m^{-2}—		%
Paquin	872	142	**-84**
Lalio	36	81	**125**
Sanchez	660	42	***-94***

* t-test results for statistical significance: Bold: P<0.05; Bold italics: P<0.01.

The striking differences are probably largely due to organic matter rich strata down to nearly 100 cm (Table 4–3). These silty deposits form nutrient rich pockets that have better moisture holding properties than surrounding sandy soils. The terrace soil

has no similar organic matter deposits, possibly explaining its lower moisture and nutrient contents and higher bulk density (Figure 4–3). These differences may reflect fleeting and localized productivity in a warm, moisture- and nutrient-limited environment. The accelerated mineralization processes from warm temperatures and frequent wet-dry and freeze-thaw cycles mean that, without occasional inputs of runoff-transported organic matter, soils may rapidly degrade and lose many cultural, hydrological, and ecological values.

The Lalio soils also show degradation with exclusion of flooding but less significantly than the Paquin soils. The lack of vegetation on the fan plot may be explained by two floods during July and August of 1999 that scoured vegetation from the site and deposited over 15 cm of sandy sediment.

The Sanchez soils have the most variable results and do not demonstrate consistent differences in nutrient or moisture contents (Table 4–7), though differences in soil profiles and vegetation between the fan and terrace soils suggest degradation from flood exclusion. In this case influx of clayey sediment from the adjacent hillslope, without occasional flushing flows from the ephemeral stream channel, may explain the apparent soil degradation. Also, the geomorphic position of the Sanchez field, including the fan plot and pedon, was lower than the Paquin or Lalio sites and below the zone where sandy sediments and organic debris are initially deposited. This may partly explain the lack of fresh fluvial characteristics.

CONCLUSIONS

The results of this study show degradation in alluvial soils associated with exclusion of flooding as may result from arroyo cutting or deliberate channelization.

While each of the three sites clearly show degradation of soils that have crucial hydrological, ecological, and cultural functions, the results are variable and more than one mechanism of degradation is suggested. At the Paquin and Lalio sites the main effect of exclusion of flooding is lack of fresh deposits of organic matter transported from uplands. Climatic conditions drive rapid turnover so that lack of fresh deposition soon leads to depletion of nutrients and degradation of other favorable properties associated with organic matter.

Results from the Sanchez site emphasize the importance of loamy or sandy sediments deposited by relatively high-energy ephemeral stream flows that spread over alluvial zones. Exclusion of the flushing action and relatively coarse sediments associated with flooding leads to accumulation of clayey materials that degrade the desirable hydrological properties of alluvial fan soils.

The variability among the three sites emphasizes the dynamic nature of the Zuni environment. The results indicate that the Paquin site is much more productive than the other two, but this is likely more a result of the timing of the investigation than intrinsic site productivity. Just like the strategies of local farmers, research should take an opportunistic approach to the variable climate and dynamic landscape if it is to provide meaningful information. Chapter five reports on Zuni methods of conserving the valuable attributes of alluvial fans.

Chapter 5: Traditional Zuni alluvial fan conservation and restoration strategies

INTRODUCTION

Discontinuous ephemeral streams that generally drain less than 500 km^2 are recognized as a distinct class of streams whose unstable, even chaotic, behavior creates problems for control and modification (Bull, 1997). Braided, alluvial reaches in these headwater systems are key components in landscape-scale hydrologic and ecological function because of rich biological productivity on-site and mitigation of floods that degrade downstream aquatic systems. Loss of depositional reaches to channel entrenchment, whether from climatic perturbation, geomorphic cycles, or intensified land use, creates a desertification feedback situation where grasslands give way to woody species which lead to increased runoff and more erosion (Abrahams et al., 1995; Schlesinger et al., 1990).

A persistent problem in designing structures for control of ephemeral stream entrenchment is the high variability of flow regimes and large amount of sediment moving through such systems (Bull, 1997). The traditional approach described in this chapter deals with this challenge by using structures that react differently to different scale runoff events. Simple brush structures are built to act as permeable, energy-dissipating check dams during frequent, channel-maintaining flows; but, during larger events, the structures wash out to act as woody debris which forms debris jams that may have major impacts on channel morphology. The work reported here describes and evaluates this approach.

Though relatively small in scale, ephemeral streams drain extensive areas, making

up a substantial portion of the world's water resources (Davies et al., 1994). Degradation of larger perennial or intermittent rivers is, to great extent, a cumulative effect of entrenchment in numerous ephemeral tributaries. While their small scale make conservation and restoration relatively feasible individually, their great extent limits ecosystem-scale effectiveness because most efforts rely on capital-intensive techniques including engineered designs and heavy equipment (Gellis et al., 1995), or on simpler methods that are nonetheless labor intensive and require off-site materials such as logs, stone riprap, or concrete (DeBano and Heede, 1987).

For ecosystem-scale impacts, solutions should be as extensive as the problems they seek to address. An ideal approach to protecting and restoring alluvial reaches in ephemeral stream courses would effectively reduce stream power over a wide range of flow scenarios, utilize natural materials available on-site, require only hand labor, and allow rapid, extensive implementation and maintenance by local people with first-hand interest in conserving resources. This paper reports work initiated and led by a group of Zuni Tribal members determined to include local traditional knowledge in current dialogs on landscape restoration (Albert and Trimble, 2000) and, ultimately, to give local people a voice in natural resource issues on their reservation.

Agricultural Native American tribes in the Southwest are known to have depended on unincised fluvial systems for millennia (Damp and Kendrick, 2000; Plog, 1997) but their knowledge is all but ignored in literature about arroyo management. Reagan (1924) suggested that prehistoric erosion control activities in northeastern Arizona stabilized landscapes from 12th century Anasazi abandonment until 19th century Anglo-American settlement. Bull (1997), in his comprehensive paper on complexity and

variability in ephemeral stream systems, recognizes that "indigenous farmers of southwestern North America used channel-fan reaches to grow their crops in a manner that promoted infiltration of streamflow and deterred channel entrenchment" while modern land use activities often have the opposite effect.

Acceptance of complexity and variability in natural systems along with recognized failure of conventional management approaches (Botkin, 1990) is slowly raising interest in what has become known as "traditional ecological knowledge and wisdom" (Berkes et al., 2000). Investigations in ecology (Ellis et al., 1993) and geomorphology (Graf, 1988) recognize that the drier the system, the more variable and unpredictable is its behavior. Traditional approaches often emphasize flexibility through opportunism, adaptability, and manipulation of perturbation-recovery cycles, principles now being incorporated into modern management systems (Berkes et al., 2000; Ellis and Swift, 1988; Scoones, 1999; Westoby et al., 1989).

Seeking Stability in an Inherently Unstable Stream System

Sediment yield is at its highest in semiarid climates with approximately 300 mm precipitation (Langbein and Schumm, 1958). Arid climates generally lack frequent enough runoff to move sediment while humid climates support sufficient vegetation to hold soils in place. Many semiarid climates are characterized by long dry periods punctuated by intense pulses of landscape-modifying sedimentation and erosion (Bull, 1997; Graf, 1988). Such variability means that dryland fluvial systems defy accepted hydrological principles such as bankfull or dominant discharge that are thought to shape and maintain channels (Graf, 1988). Dominant discharge is defined as the event with a combination of magnitude and frequency (typically 1.5 to 2 years) that, over the long-

term, maintains channel morphology and does the most geomorphological work (Graf, 1988). Flow resistance is at its minimum so the channel operates most efficiently for movement of water and sediment at this level. Although channels may be shaped by rarer, higher magnitude events, morphological features like floodplains (no matter how narrow), point bars, and other alluvial features are controlled by these relatively frequent scouring flows (Gordon et al., 1992; Graf, 1988). Graf (1988) points out that, no matter how tempting it is to link frequency, sediment transport, and floodplain processes in the concept of a "dominant discharge," unpredictably variable conditions in dryland streams preclude simple correlation (Graf, 1988:104). Still, relatively high frequency events in the 1.5- to 10-year frequency range, are thought to move more sediment over the long term than large, low frequency floods, though Davies et al. (1994) suggest that as much as 60 percent of sediment is moved by events with recurrence intervals of 10 years or more. Dominant discharge-scale events create more-or-less steady downstream movement of bedload while large, powerful floods cause sudden drastic changes to channels and alluvial fans. For this report "dominant flow" refers to bank full or dominant discharge scale events and "flood flow" refers to larger events (>~10 year recurrence interval).

This dichotomy in fluvial processes between two ends of the flow spectrum creates problems for structural erosion control efforts. Structures built to withstand large floods are often destroyed by incessant impacts of dominant flows. Blocking the "river of sediment" moved by dominant flows causes siltation upstream and channel incision downstream, as "hungry" runoff reestablishes equilibrium between gradient and bedload (Gellis et al., 1995; Graf, 1988). Rigid check dams built to control impacts of dominant

flows are often breached, flanked, or undercut during powerful flood flows because they constrict flow.

Yet, permanence and one-size-fits-all design is what is sought in most efforts, including large-scale earthen dams (DeBano and Heede, 1987; Gellis et al., 1995) and smaller labor-intensive log, stone, or concrete structures (DeBano and Heede, 1987; Seehorn, 1992). Gellis et al. (1995) evaluated large earth and rock structures on the Zuni Reservation built with heavy equipment by government agencies and brush structures built by a 1970's Youth Conservation Corps team under the leadership of an elderly Zuni farmer. They found that 28 of the 47 large, heavy-equipment-built structures had breached and 31 were more than half filled with sediment. In contrast, only five of the 23 hand-built brush structures had failed and the remaining were fulfilling their intended purpose. Failures were attributed to lack of maintenance, but the hand-built structures would clearly be much easier to maintain than the large dams.

Neglect of the traditional Zuni approach to soil and water conservation may be due to a perception that simple, small-scale techniques are irrelevant to modern, large-scale erosion problems. However, improved understanding of the dynamic, unpredictable nature of dryland stream systems makes the approach described here appealing from technical hydraulic and hydrological standpoints. The techniques can be implemented across large areas in ways that may impact whole watersheds. The approach does not presume to predict the power of flow events with one-size-fits-all design, but rather functions differently under different flow conditions.

The Politics of Erosion Control

In 1933 a Zuni-based licensed trader named Masters, with long-term expertise

and interest in erosion control, criticized Bureau of Indian Affairs erosion control techniques and recommended that BIA engineers visit Zuni cornfields to, "see how this work should be done" (Cleveland et al., 1995). The Zuni approach stems from perceptions of erosion in particular agricultural and environmental situations. As such, the work addresses *on-site* problems that threaten specific agricultural fields or grazing areas. In so doing, farmers' activities maintain channel discontinuities where ephemeral streams store sediment and runoff water, and in the process address *off-site* issues that are the concern of agency-driven efforts.

Failures of large-scale conservation efforts run by national or international agencies have received increasing worldwide attention (Blaikie and Brookfield, 1987). Neglect of local values with respect to natural resources, erosion, and conservation means that many government-sponsored efforts conserve off-site resource values at the expense of local ones (Bocco, 1991). As often as not, however, misconceptions of local climatic variability and erosion processes result in the failure to conserve off-site values as well (Blaikie, 1995). This creates situations where government-implemented conservation lacks participation and support of local people, and often fails because locals have neither interest in nor ability to maintain them (Siebert and Belsky, 1990). Large earthen sediment retention structures, for instance, are built with the goal of protecting downstream reservoirs from sedimentation. Though sometimes beneficial, these structures often contradict local priorities of protecting traditional farming or grazing areas. Their large scale means that local people are powerless to maintain.

This chapter addresses a traditional approach to maintaining and restoring hydrological connectivity between ephemeral channels and alluvial fans. The approach

hinges upon permeable check dams that can be built, maintained, or replaced very rapidly so that whole arroyo systems can be treated by hand in relatively short time periods. The approach arises from local peoples' understandings of fluvial processes. As such, the structures function differently under different flow conditions.

STUDY SITES, TREATMENTS, AND MONITORING METHODS

The Zuni Indian Reservation lies in the southeastern part of the Colorado Plateau at 1800 to 2400 m elevation. Vegetation on mesa tops and slopes is dominated by P-J (pinyon [*Pinus edulis*]-juniper[*Juniperus* spp.]) woodlands and alluvial valley margins by big sagebrush (*Artemisia tridentata*), blue grama (*Bouteloua gracilis*), and western wheatgrass (*Agropyron smithii*). Predominance of loosely indurated Cretaceous sandstones and shales in erosive, semiarid conditions creates an abundance of unconsolidated sand and finer valley fills (Graf et al., 1987). Fluvial channels of tributary alluvial fans are typically sandy and smooth. Combined with the Southwestern climate with its distinct late summer convection storms, the fine alluvial materials and sparse vegetation cover create dynamic fluvial environment characterized by movement of large amounts of sediment (Balling and Wells, 1990; Lagasse et al., 1990; Wells et al., 1983).

Study Sites

Three sites on the Zuni Reservation were chosen and surveys of arroyo profiles and cross-sections were conducted prior to treatment and at the end of the study period. The Laate site is an ancient Zuni peach orchard high on a step-like bench of the Zuni Sandstone (Figure 5–1). Its position on the lee side of a large mesa facilitates deposition

Figure 5–1. Sketch map of part of Laate peach orchard by Fred Bowannie, Jr., showing ephemeral stream system treated with erosion control structures. Scale is approximately 600:1.

of wind-blown sand. An ephemeral stream crosses the peach orchard and production likely depends upon stormwater flows spreading and infiltrating the sandy soils. The stream course has a tendency to incise however, and requires occasional maintenance to retain both sediments and runoff. This site was actively maintained and produced peaches until the mid 1960's, after which it was abandoned until an elderly farmer began caring for the remaining live trees and propagating new ones about 10 years ago. This site was selected because of the cultural significance of the few remaining Zuni peach orchards and the threat to the living trees posed by the incising channel. The incised

channel was treated with structures in 1996 and determined baseline elevations during the 1999 post-treatment survey by digging through sediments to the 1996 surfaces (identifiable by plants, soil surfaces, and structure bases).

The Lalio site is a partially incised rainfed cornfield which is farmed by hand by the Lalio family. The cornfield lies in a discontinuity of an ephemeral stream channel that drains a small, narrow watershed. An incised arroyo cuts into the field about a third of the way from the original boundary. Large headcuts downslope from the field connect the drainage way to Cheama Wash, a tributary of the Zuni River (Figure 5–2). By June, 1998, a continuous rill had formed through the field, partly the result of two erosive flow events in 1997. This site was selected because it represents the threat to traditional rainfed fields posed by arroyo cutting. Baseline surveys were conducted and structures were built in the arroyo in May and June of 1998.

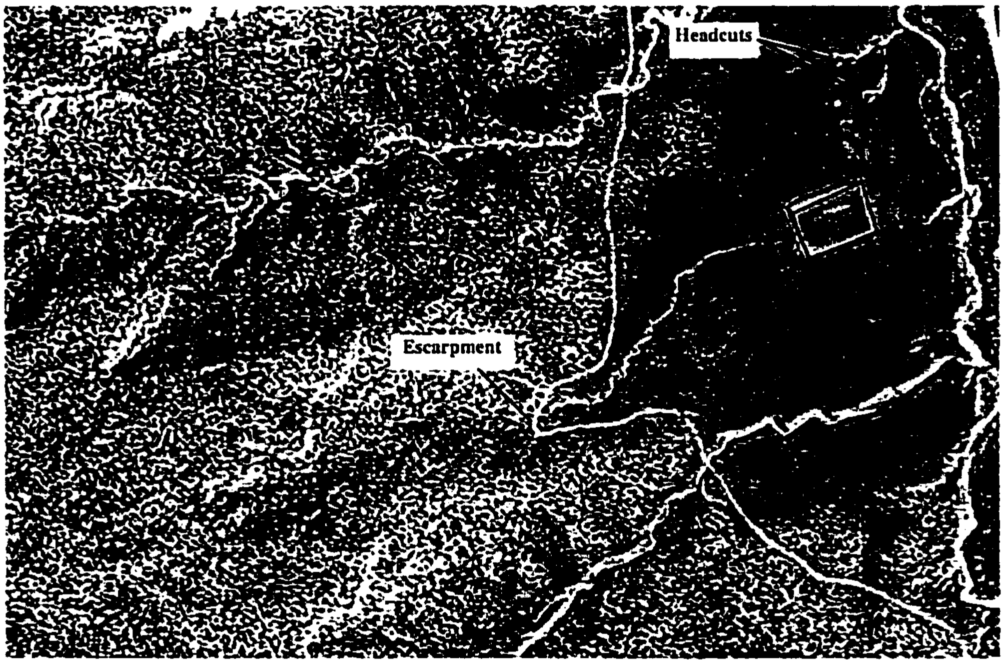

Figure 5–2. Lalio site. 1988 aerial photograph. Structures were placed from the escarpment downstream to the upper one third of the cornfield. Scale is approximately 14,400:1.

The Quandelacy site is an actively lengthening and deepening arroyo that cuts through rangelands above the Pescado farming district (Figure 5–3). This site was selected because it is typical of rangeland degradation. Work began in June of 1999.

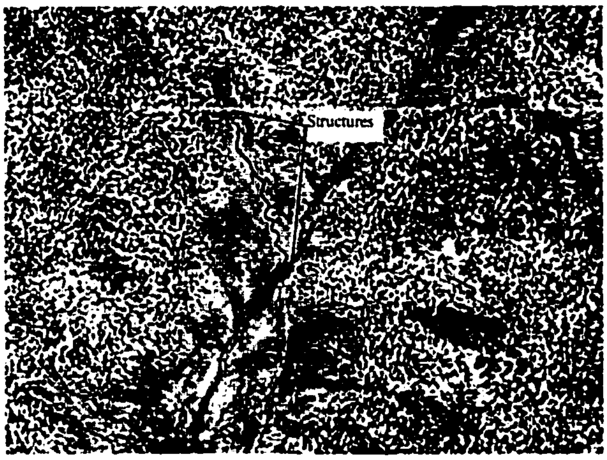

Figure 5–3. Quandelacy site, 1988 aerial photograph. Structures were placed in tightly meandering arroyo from the edge of the bedrock uplands to its confluence with a larger, discontinuous system. Scale is approximately 14,400:1.

Treatments: Construction Methods

Structures were installed by a crew led by individuals with life-long experience in this type of traditional erosion control. The workers used axes, shovels, and posthole diggers. The four leaders each favored particular methods, but all felt strongly that keying-in structures creates weakness that diverts strong flows under or around the structures. They would rather have the easily replaceable material wash away than force the flow around and thereby exacerbate erosion problems.

The workers estimated structure spacing required based on particular channel conditions including sinuosity, gradient, and width. Locations with natural energy-reducing features, such as tight bends, knick points, or obstructions (i.e., rock outcrops or bank vegetation) were preferred. Availability of nearby woody material also played a

role. The average spacing of the completed treatments at each site was much closer than Heede's (1976) "spacing rule" for grade control check dams, which is based on channel gradient and dam height.

The workers explained that their erosion control approach doubles as range improvement because pruning trees improves sight distance for sheep-herding and increases forage production under canopies, while sagebrush removal is believed to stimulate grass growth. Clearing brush and trees and controlling gully erosion in farming and grazing areas is often the motivating objective behind erosion control activities; material is disposed in arroyos to prevent incision. During clearing projects, arroyo reaches may be completely filled with woody debris.

Brush Piles

Limbs of pinyon and juniper trees and whole sagebrush plants were piled in channels with larger stems pointing downstream (Figure 5–4). Material was stomped down repeatedly as piles were being built. Stones or larger logs were used sparingly to compress and hold piles in place only if these materials were readily available. In P-J woodlands the material consisted of lower limbs from 2 to 15 cm diameter. In areas dominated by big sagebrush, whole plants were piled in the arroyos. The sagebrush dominated reaches of the Lalio and Quandelacy arroyos had slot-like channels with width:depth ≤ 1. Large amounts of sagebrush were packed into these channels over distances up to 30 m by stomping down layer after layer. Shallow rills through the Laate Peach Orchard and the Lalio cornfield were filled with fine branches or woody material such as broom snakeweed (*Gutierrezia sarothrae*). This was the most rapid method used and had the objective of placing as much debris as possible into the channel.

Check Dams

Simple check dams of interwoven woody material were slightly more intensive than the simple brush piles. After a large pile of material is thrown into the arroyo, the largest, longest limbs or stems are lain across the channel, with brushy tops in alternating directions, in a pile about 0.5 to 1 m high. The smaller, fan-like limbs of pinyon and juniper (pinyon is preferred) are jabbed and woven into the pile so that when finished the small branches and leaves present a dense mat of fine woody material to the upstream direction (Figure 5–5). When time allows, these dams are reinforced with three posts cut from P-J stems and set immediately downstream in an H- shaped structure (one post set on each side of the channel at an upstream angle and one wired across between them).

Post and Wire Methods

In this method, two rows of poles about 1 m apart cross the arroyo channel and are set into the bed. Sagebrush and P-J branches are packed between the poles to create a barrier about 1.5 m high. The tops of the poles are then wired together. These methods require more effort in sorting and trimming woody material, setting posts, packing brush, and wiring braces together. They were more carefully located in relatively wide, low energy reaches, at points immediately below sharp bends, or in series of two to three structures. Construction is still relatively rapid, because, except for a small amount of wire, all materials are immediately at hand. Each of these structures was built by one worker and took two to three hours for structures up to 7 m long.

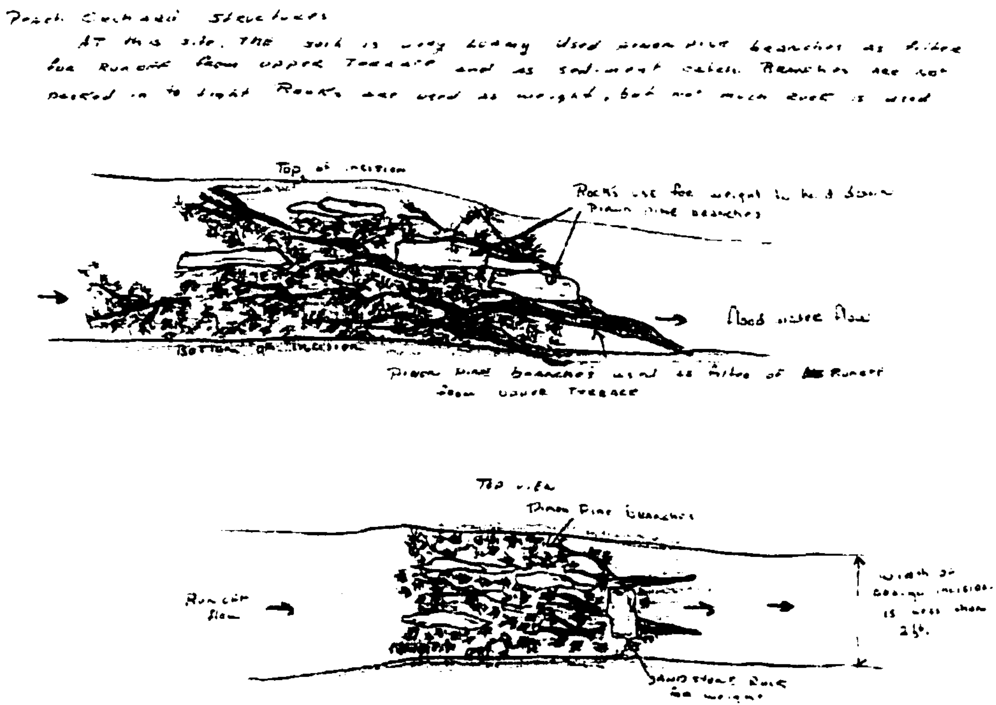

Figure 5–4. Brush-pile structures. Branches oriented with larger stems downstream; rocks used for weight and compression. Drawings by Fred Bowannie, Jr.

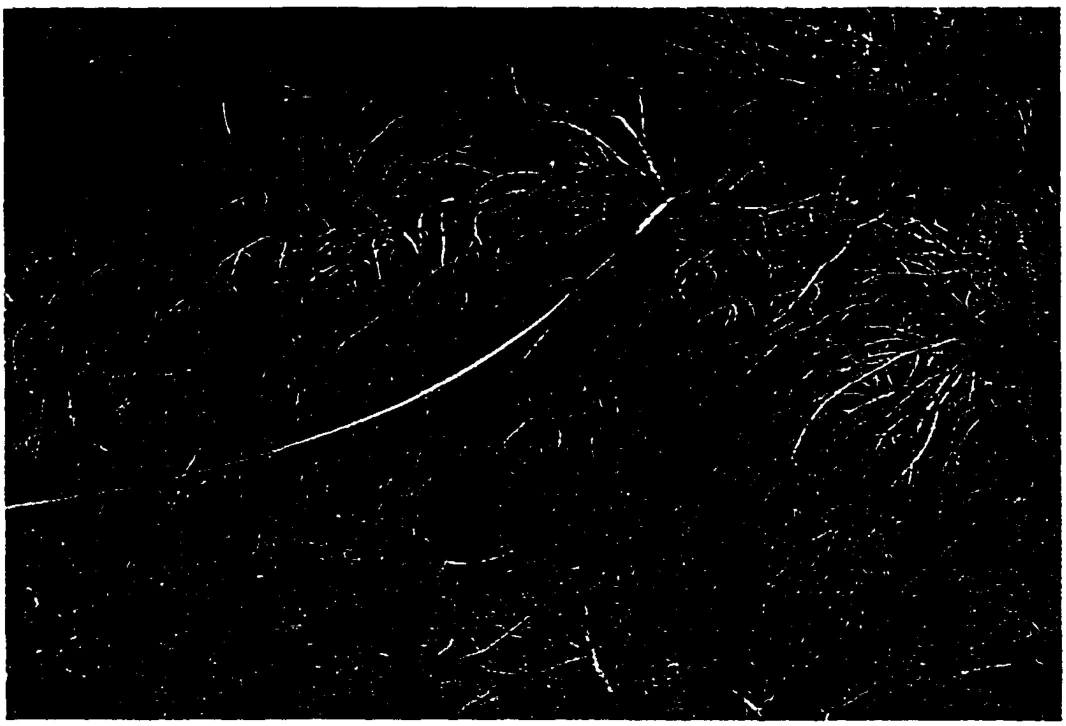

Figure 5–5. Simple brush check dam structure. Small pinyon branches are secured in larger branches stacked length-wise across the channel. Tape follows thalweg.

"Pungie" Posts

Pungies posts consist of clusters of larger P-J limbs and stems set into the arroyo bed to form comb-like structures that capture woody debris and create reinforced debris jams during flow events (Figure 5–6 and Figure 5–7). The posts are set at least 60 cm into the ground angled upstream. Placement is downstream from "brush pile" structures and upstream from other types to protect and reinforce them. Some of the "pungies" were reinforced with post and wire braces. Part way through the season the workers decided to alter this method by leaving the fine top branches on the posts with the thought that if they eventually wash out the fine materials will add to the effectiveness of the woody debris when it is redeposited. Steel T-posts were used as pungies in one arroyo reach.

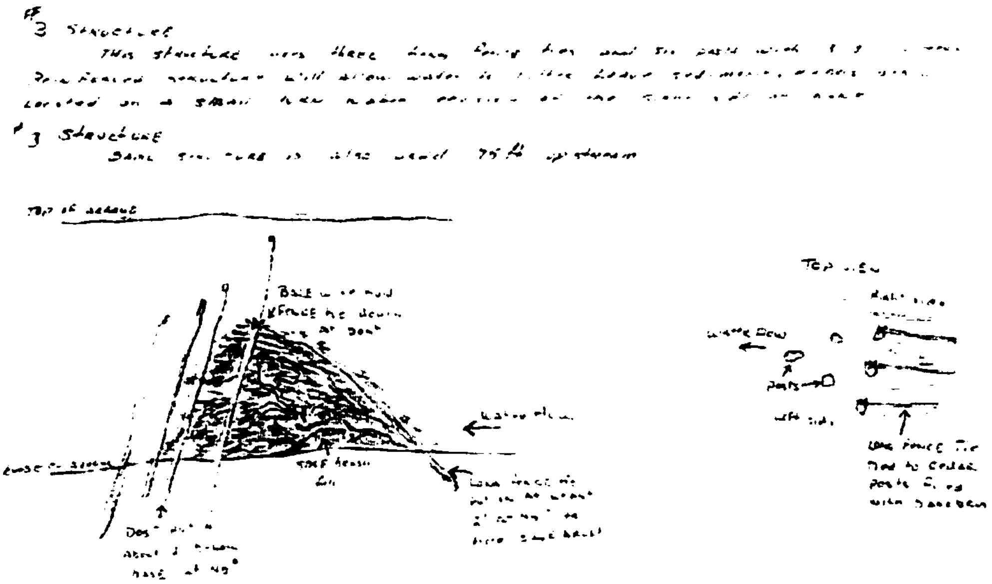

Figure 5–6. Brush pile reinforced with pungi posts. Drawings by Fred Bowannie, Jr.

Figure 5–7. Pungie posts immediately upstream from post-and-wire structure in Lalio arroyo.

Measurement and Monitoring

Pre- and post-treatment surveys were done with level, rod, and tape as described in Harrelson et al. (1994) with several photo points along each arroyo. Post-treatment surveys were repeated after floods at the Lalio and Quandelacy sites in 1999 and included elevations of thalweg, structures, banks, and water levels identified by high water marks on the arroyo banks. Members of the crew recorded labor input, wrote descriptions of structures, sketched maps and structure designs, and photographed construction.

Rainfall volume and intensity was recorded every 15 minutes during the 1999 season at a tipping bucket rain gauge located approximately 2 km from the Lalio site and operated by the Zuni Conservation Project. Recurrence intervals for 1999 rainfall events were determined using rainfall intensity-duration-frequency curves for Albuquerque,

New Mexico (U.S. Weather Bureau, 1955). Recurrence interval for flow events was determined by, first, estimating peak discharge using Manning's equation with parameters measured during post-treatment surveys. These values were compared to peak discharges derived from USGS equations for 2- through 100-year recurrence interval events (Thomas et al., 1997).

RESULTS AND DISCUSSION

As a two-year study of flood behavior in watersheds where low flow may be generated an average of every 1.5-years (Chapter 1), I expected this to be a descriptive report of traditional methods and did not anticipate substantial hydrological results. The summer of 1998 lived up to our low expectations, with only one minor flow in the Lalio channel that infiltrated before reaching the cornfield. However, the 1999 summer season was remarkably moist with three major floods and multiple lower flows at all the sites. Results are presented from all three sites but the following discussion focuses mostly on the Lalio site because it was most active and because of its proximity to ZCP's rain gauge.

Figure 5–8 shows 1999 daily rainfall at the ZCP gauge. The July 5 rain event dropped 18 mm in less than 15 minutes, at least a 25-year recurrence interval rain event (U.S. Weather Bureau, 1955), and the resulting flow, estimated from Manning's equation (Table 5–1), exceeded the 100-year recurrence interval flow for the Lalio watershed (Thomas et al., 1997). The remainder of July brought several substantial flow events in the 5 to 25-year recurrence interval range, and on August 2 an intense thunderstorm generated a 100-year flood in the watershed immediately to the west of the Lalio site (personal communication, Kirk Bemis, Zuni Conservation Project, 1999). This storm also

produced intense runoff at the Lalio and Quandelacy sites. On August 27 another thunderstorm dropped 18 mm in less than 45 minutes at the ZCP gauge, which generated a powerful runoff event from the primed soils in the Lalio watershed.

Repeated, unusually powerful events, along with several "dominant discharge" flows of more frequent, channel maintaining magnitude, provided the unique opportunity to observe effects of the structures almost immediately after construction and to monitor their impacts over a wide range of stream flows. The traditional treatments reacted very differently to dominant discharge-scale events than to large floods.

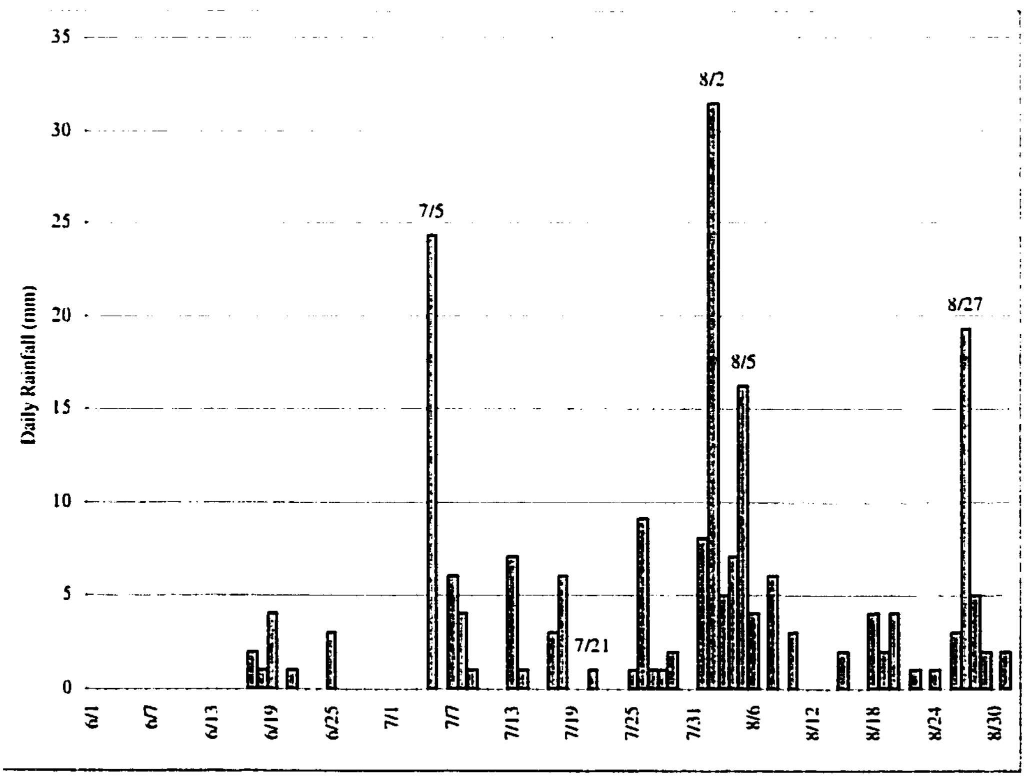

Figure 5–8. 1999 daily rainfall near Lalio site. July 5 event peaked at ≥ 72 mm hr^{-1}. Courtesy of Zuni Conservation Project.

Table 5–1. Flow estimates for July 5, 1999, flood and pre-and post-treatment arroyos.

Parameter	Units	Lalio 7/5/99	Lalio overbank, pretreatment	Lalio overbank, post-treatment	Quandelacy overbank, pretreatment	Quandelacy overbank, post-treatment
Station*	m	510	320	320	130	130
Slope		0.02	0.02	0.006	0.035	0.01
Cross-sectional area	m^2	1.9	4.5	1.08	1.94	0.58
Hydraulic radius	m	0.31	0.58	0.20	0.44	0.15
Manning's n**		0.017	0.017	0.017	0.017	0.017
Peak discharge	m^3s^{-1}	7.31	26.04	2.21	12.35	0.80
Recurrence interval***	years	>100	never	2	never	5

* Meters from lower end of longitudinal profile.

** Calculated using Limerinos equation, assuming a grain size d_{85} of 2 mm (85 percent of the channel bed particles are smaller than 2 mm diameter) for the sandy channel beds (Gordon et al., 1992). Graf (1988) cites potential usefulness of Strickler's equation for dryland rivers, but in this case Limerino's gives a more conservative (higher) estimate of Manning's n, though Graf (1988) gives 0.02 as a low-end estimate for smooth, sandy channels.

*** Estimated using regression equation presented by Thomas et al. (1997).

Structure Impacts on Dominant Flows

Structures at all three sites acted as permeable check dams during dominant flows. The fine, densely packed woody material in the channel, reinforced with "pungie posts" and braces, caused temporary pools that dissipated stream power (Figure 5–9c and Figure 5–10). The simpler brush pile and check dam structures built in June of 1998 at the Lalio site showed evidence of similar behavior with some ponding and sediment retention after minor events in 1998. The brush pile structures at the Laate Peach Orchard retained sediment as indicated on Figure 5–11.

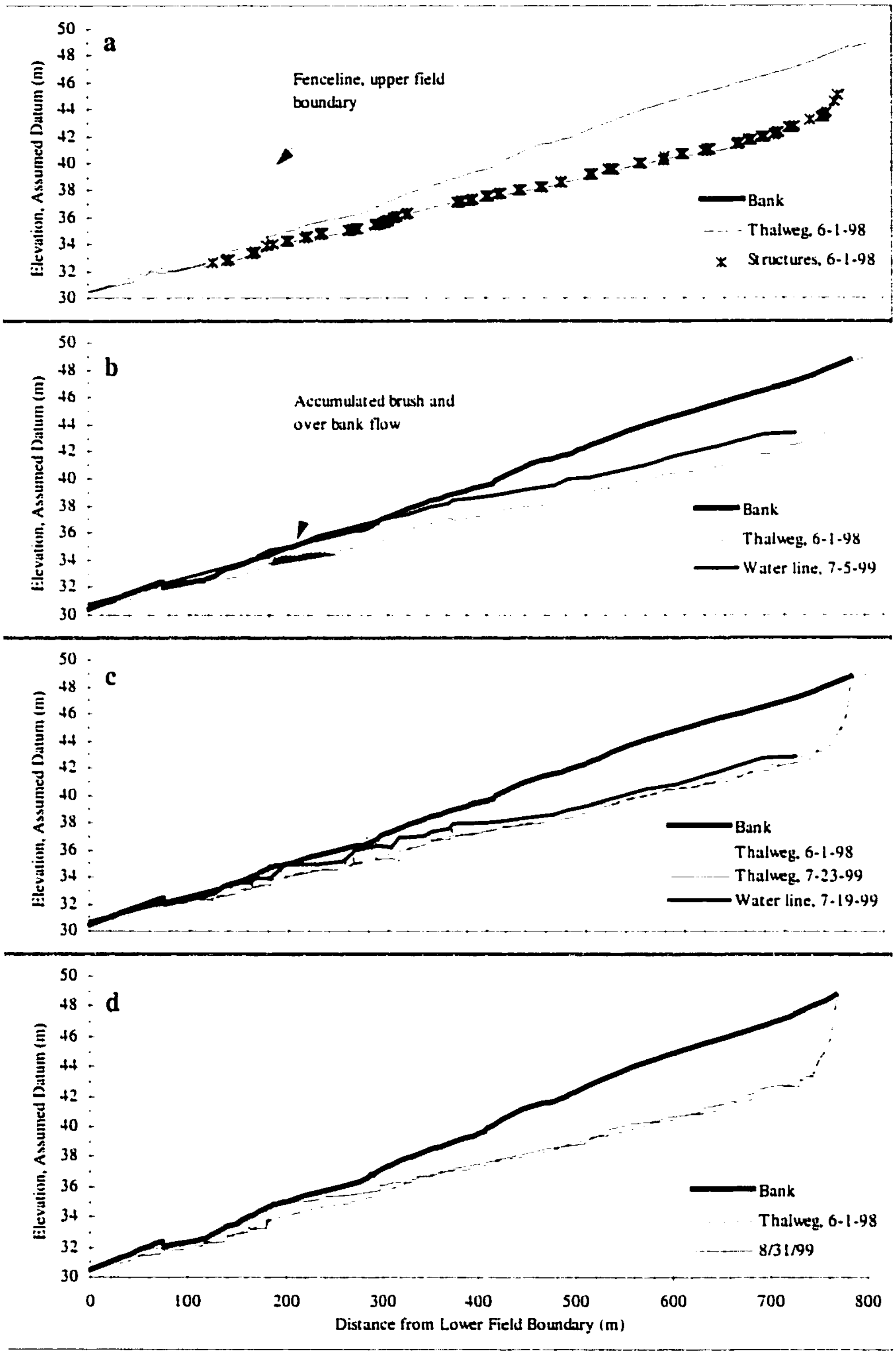

Figure 5–9. Lalio site longitudinal profiles. Peaks in (c) represent structures installed after the July 5, 1999 flood.

Figure 5–10. Sagebrush and pungie check dams above Lalio field shortly after peak discharge on July 18, 1999. Note stepwise waterlines behind structures and effect of brush clearing along banks.

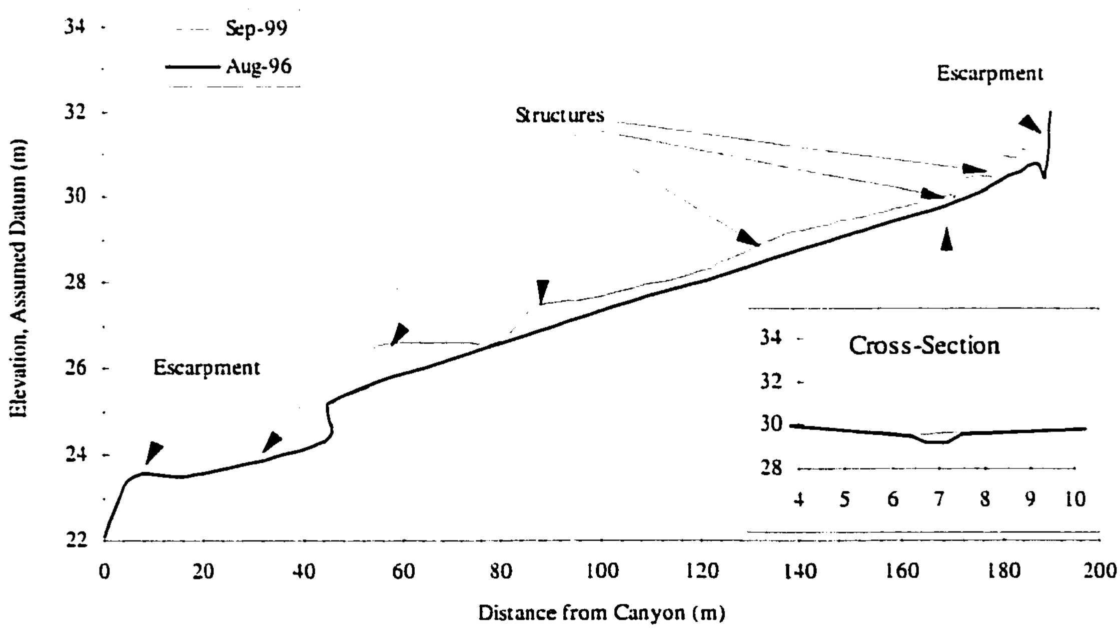

Figure 5–11. Laate peach orchard longitudinal profile. Shows thalweg elevation before and after treatments.

Temporary, permeable structures have not received a great deal of attention in erosion control literature and are not discussed in channel and riparian restoration guidelines (DeBano and Heede, 1987; Seehorn, 1992). Gordon (1992:467) briefly discusses the use of debris from pruning and "wicker spiling hurdles" (check dams built from fine woody material woven around a row of vertical posts) to help control bed and bank erosion. ZCP uses a variation of "wicker spiling hurdles."

The U.S. Army Corps of Engineers has worked with permeable check dams made of synthetic materials designed to wash out during high flows before damaging channel beds and banks (personal communication, Dr. Phillip King, New Mexico State University, 1998). Bioengineering, the use of living materials, especially willows, woven into mats and used as bank protection, has some similarities with the permeable dam approach in that fine mats of woody material dissipate the energy of flows rather than abruptly stopping or diverting them.

Materials included in U.S. Environmental Protection Agency's participant manual for the Tribal Unified Watershed Assessment Workshop describe techniques very similar to the "post and wire" techniques used in this study (U.S. Environmental Protection Agency, 1999). This publication credits the design to a 1935 CCC publication. Many elderly Zunis worked on erosion control projects of the CCC in the 1930's, suggesting that parts of some techniques may have been adopted and handed down to the workers that led this project.

The temptation in many designs is to attempt permanence by keying structures in to bed and banks and using as much rock as can be hauled in. In contrast, the workers that led this project, as well as other Zunis interviewed for Chapter 1, are generally

against the use of stones except sparingly to compress piles of woody material. These workers believe that stones placed on the fine, unconsolidated channel beds speed and increase stream power while their impermeability forces and constricts flows causing undercutting or flanking of structures through the fine alluvium of arroyo beds and banks.

Impacts on Flood Flows

During the three higher magnitude floods of 1999, the channel treatments did not behave as check dams at all, but instead, the woody material was transported and deposited in debris jams that grew larger with each flood. The debris jams greatly impacted channel morphology and flood behavior at the Lalio and Quandelacy sites. In this case, the treatments are analogous to large woody debris known to be critical to channel morphology in woodland streams.

In woodland streams, large woody debris is a primary determinant of channel morphology, forming pools and regulating transport of sediment, organic matter, and nutrients (Fetherston et al., 1995; Lisle, 1995). In small streams large woody debris are responsible for as much as 87 percent of channel sediment storage, with 39 percent or more of the individual pieces forming depositional sites (Fetherston et al., 1995). Such depositional sites are colonized by vegetation which further impacts flow events.

Traditional methods described here supplement woody material naturally deposited in channels, greatly increasing the likelihood of debris jams that impact channel morphology. Workers understand both the futility of fighting large flow events and the effectiveness of large amounts of woody debris. This understanding drives their notions about rapidly placing as much material as possible into the channels with little concern about constructing check dams or keying in structures.

Figure 5–12 show the impacts of the debris jam that formed during the July 5 flood and grew with the August 2 and August 27 floods. After the August 27 event the debris jam was higher than the arroyo bank and over 30 m in length. It caused backfilling of the arroyo for 140 m upstream, almost completely filling it just upstream from the debris jam. Overbank flow started over 200 m upstream from pretreatment overbank flow and floodwaters spread through the sagebrush north and south of the channel depositing a layer of sand up to 20 cm thick.

After the August 27 event the original channel connecting the cornfield to the watershed remained, although much reduced in depth and gradient, so low to moderate flows followed the original channel into the cornfield but excess water and sediment from large events are diverted over the arroyo banks onto parts of the alluvial fan not flooded for many years. Figure 5–13 summarizes the effects of the flood events. Fresh layers of sandy sediment should improve infiltration and forage production in these sagebrush-dominated areas. The area flooded during the August 27 event was at least four times larger as a result of the treatments in the channel.

Comparison of the probability of over bank flows before and after the treatment suggests that connectivity between the channel and alluvial fan has been reestablished. Prior to treatments, a discharge of 26 m^3s^{-1} would have been required to reach the top of the arroyo bank at 320 m along the profile. This is virtually impossible in this size watershed (Thomas et al., 1997). After combined effects of treatments and flood events in 1999, over bank flow would occur at approximately 0.2 m^3s^{-1}, a two-year recurrence interval peak discharge at the Lalio arroyo (Table 5–1).

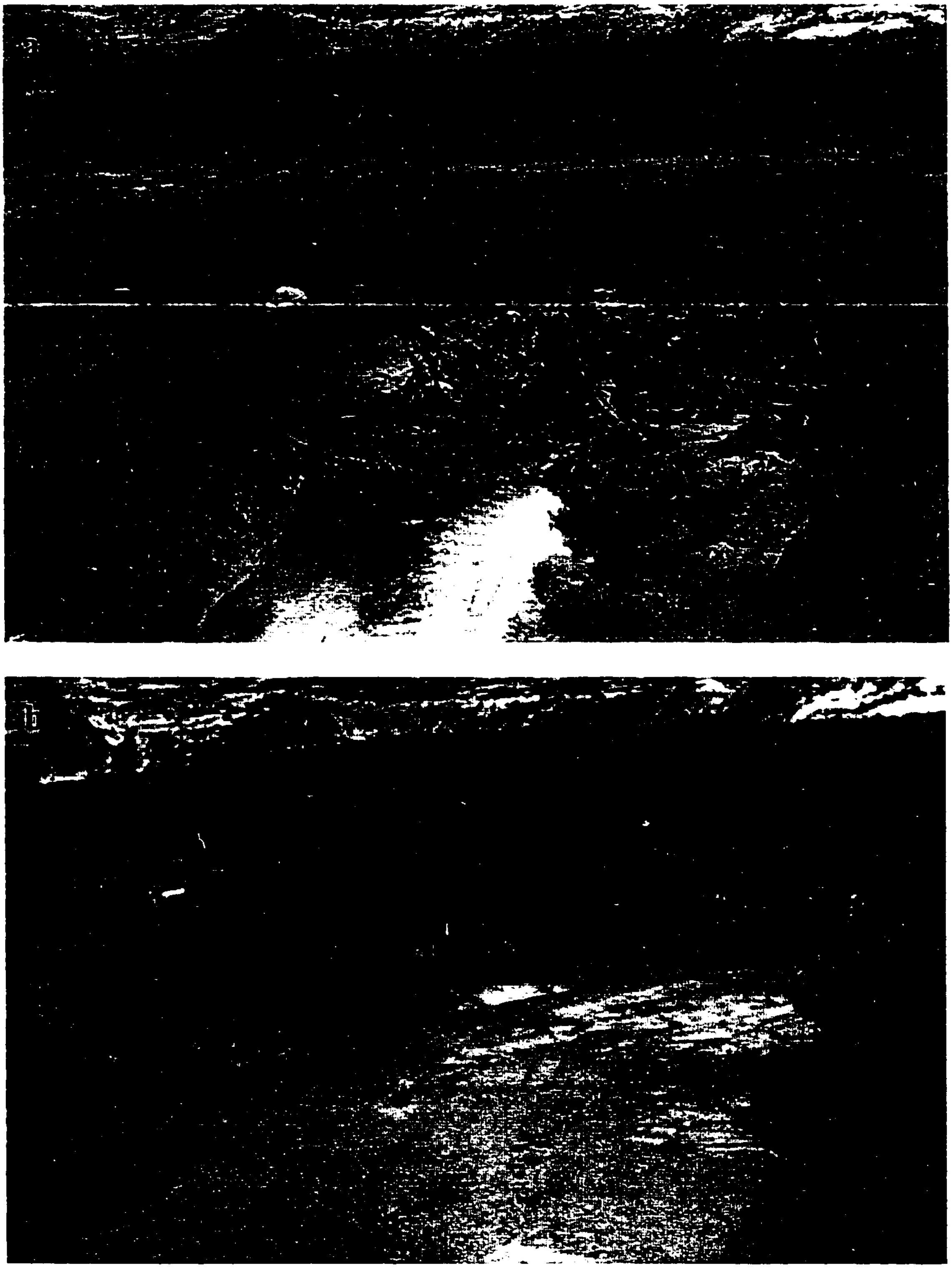

Figure 5–12. Lalio fenceline debris jam on July 18 (a) after backfilling had begun with the July 5 flood, and August 27 (b). Arrows point the same dead juniper tree in each photograph.

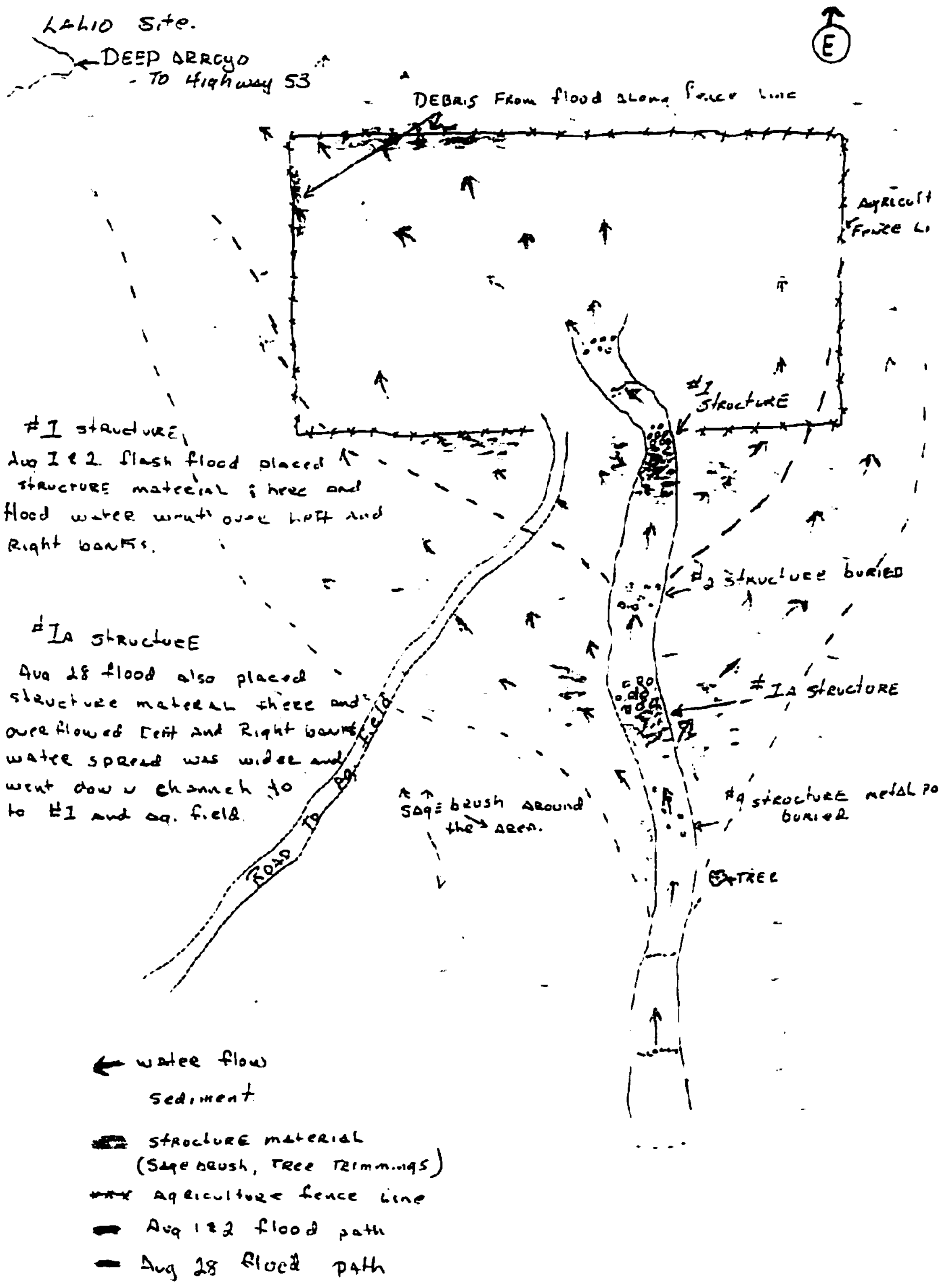

Figure 5–13. Sketch map showing chronology of flood events and reaction of treatments at the Lalio site. By Fred Bowannie, Jr.

The Zuni workers expressed some concern that a strong flood could create a new channel that would miss the cornfield, though dominant flows would likely develop and maintain the present channel. They felt that continued monitoring and maintenance to ensure that the low-flow channel continued in its present course would prevent formation of a new channel.

The July 5 rain missed the Quandelacy site, but a large storm on or around August 2 brought powerful runoff that moved most of the woody material. Debris jams formed at two points along the arroyo associated with structures. One at 130 m along the channel profile (Figure 5–14) caused overbank flow and diverted most of the flood out of the channel. Again, a low-flow channel was maintained, but higher, potentially destructive flows were diverted onto sagebrush dominated rangelands far upstream from the previously flooded area. The treatment achieved connectivity between the channel and a much larger portion of the alluvial fan. Prior to treatment overbank flow from the arroyo was not possible, but after the effects of the treatment and the August 2, 1999, flood, a five-year recurrence interval event will overbank at the 130 meter point of the arroyo (Table 5–1) (estimated via Manning's equation and Thomas et al., 1997).

Labor requirements for the repeated treatments with structures (Table 5–2) show that the first treatments at the Lalio and Quandelacy sites were relatively rapid but the second treatments required more time to build reinforced pungie post and post-and-wire type structures. Although these figures are difficult to compare to other methods that rely on permanent structures, the end result of the project (315 manhours to successfully treat 1.25 km of entrenched arroyo channel) represents an economical approach, even with unusually powerful events of 1999 that necessitated repeated treatments.

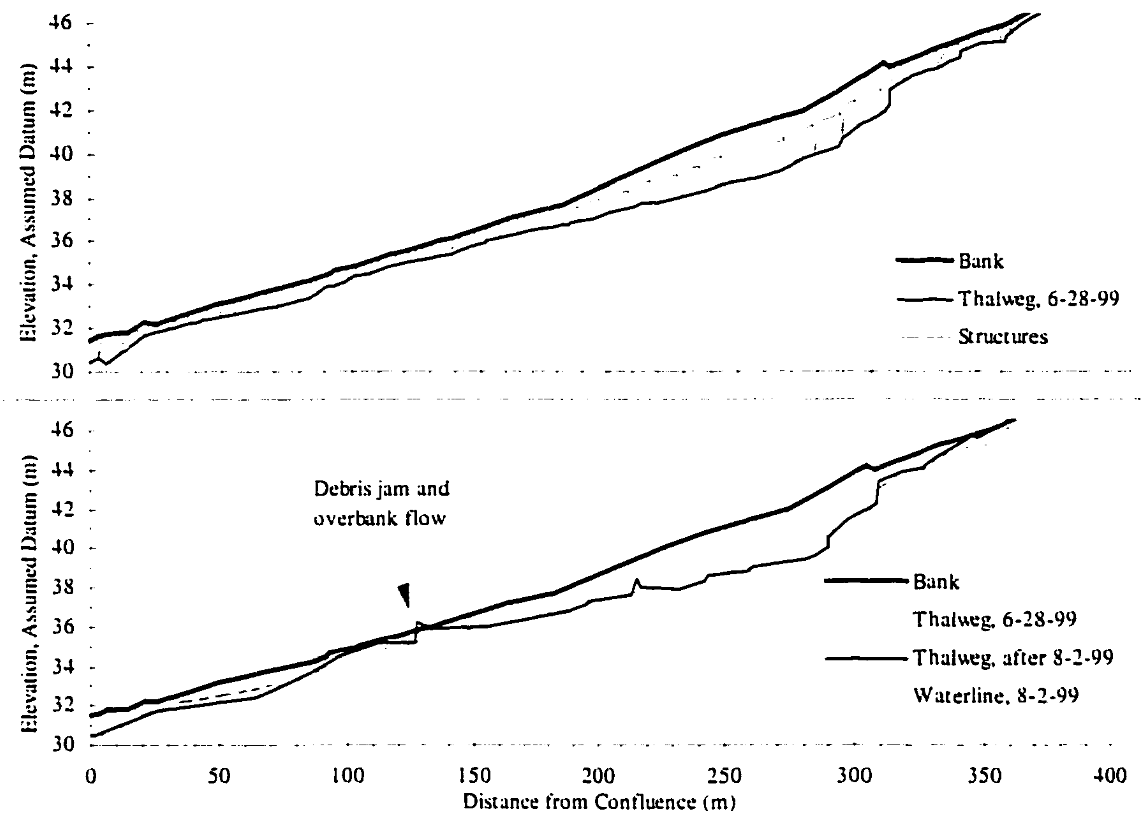

Figure 5–14. Quandelacy site longitudinal profiles.

Table 5–2. Labor requirements for arroyo treatments.

Date	Site	Crew	hours	man-hours	structures	meters	hours per struct	Hours per km arroyo
8/1/96	Laate P.O.	8	4	32	10	180	3	178
6/1-3/96	Lalio	6	8	48	35	700	1	69
7/14-16/99	Lalio	4	10	40	10	350	4	114
7/19-24/99	Lalio	4	15	60	15	700	4	86
8/4-19/99	Lalio	4	15	60	15	700	4	86
6/30-7/1/99	Quandelacy	3	13	39	41	370	1	105
8/25-26/99	Quandelacy	4	9	36	10	370	4	97
TOTALS:				**315**	**136**	**3370**	**2**	**93**
Arroyo meters treated:				**315**		**1250**		**252**

CONCLUSIONS

In general there were three types of responses associated with the treatments during different sized flow events (Table 5–3). Relative to other types of treatments, labor requirements are low and virtually no materials are needed. Labor was balanced between strengthening structures sufficiently to withstand dominant discharge-scale events and simply placing as much material as possible in the channel to act as woody debris during larger floods for which no amount of strengthening would be sufficient. Conversely, over-strengthening is believed to cause more damage when large floods take out structures. The structures acted as permeable, energy dissipaters during low to moderate-sized flow events that, left unchecked, can form continuous channels across alluvial fans. During large events the structures demonstrated a "fuse-plug" reaction, washing out before causing damage by constricting flows. The materials then acted as woody debris, increasing likelihood of channel modifying debris jams. Both responses have hydraulic and hydrologic benefits to streams.

While the outcomes of the arroyo treatments, including energy dissipation and backfilling with sediment, could have been achieved with other, more conventional methods, the speed with which long arroyo reaches can be treated and the lack of adverse impacts during high flow events are attractive features not duplicated by other methods. Local people possess awareness of the range of variability in their dynamic environment and have developed approaches for maintaining desirable alluvial conditions under a broad range of possible climatic conditions.

Table 5–3. Impacts of traditional structures under different flow regimes.

Type of Flow Event	Flow Magnitude/Frequency	Behavior of Structures
Minor	≈ 1-year recurrence interval	No effect or slight sedimentation and scour. Runoff flows through permeable structures.
Dominant discharge	~1.5- to 10-year recurrence interval	Structures cause temporary ponding and dissipate stream power. Cause sedimentation above and slight scour below, unless spaced so that temporary pool extends to next structure upstream. Protect alluvial fans from additional incision.
Large floods	≥ 50-year recurrence interval	Structures give way and act as large woody debris, causing debris jams and sedimentation, which reduces depth of flows so that "bank-full" flows become "overbank" flows. Reconnect ephemeral channels to larger areas of alluvial fans.

The fact that either scenario; persistent permeable check dams or woody debris moved by floods, creates a positive outcome of the labor expended is an attractive aspect. Although the workers expressed surprise at the drastic channel changes caused by their treatments, an important part of their approach, which they repeated often, is that once the woody material is in the arroyo "Mother Nature will move it to where she wants it." Contrary to conventional approaches to erosion control, the Zuni method takes a "fuse-plug" approach in that structures are expected to wash out during large and powerful flows that would likely flank or breach more "permanent" structures.

In summary, important components of this traditional Zuni approach to erosion control include:

1) Use of only materials directly available on-site to speed construction, prevent additional erosion from haul roads, and improve surrounding grazing lands by clearing brush and pruning trees;
2) Woody materials are tightly packed with fine branches upstream and, where readily available, weighted down with stones or logs. The fine mesh of the compressed woody material creates an effective but permeable barrier which does not affect small, unerosive flows but slows and reduces energy of "dominant discharge" type, 1.5- to 10-year frequency events;
3) Structures built to withstand "dominant discharge" flows without keying them in to banks react to larger floods as "fuse-plug" dams, preventing damage that occurs when over-strengthened structures constrict powerful, erosive flows;
4) Simplicity, rapid construction, and low cost are critical components in this extensive approach to an extensive problem.

Perhaps most importantly, this approach represents an effective local solution to a local problem where outside efforts based on outside impressions of the problem and the environment have failed. Social aspects of traditional ecological knowledge as empowerment in environmental and development issues have been recognized since at least the 1980's. More recently traditional ecological knowledge is valued for more complete and accurate environmental understanding and more effective management, conservation, and restoration approaches than have been achieved with conventional science and engineering approaches.

Conclusions and Implications

Results of this research emphasize structure and function of watershed components that contribute to sustained productivity and functional values of alluvial fans. Alluvial fans of small, tributary watersheds are used in traditional farming but are also key landforms in integrity of dryland ecology and hydrology. The improved understanding offered here could contribute to better management that conserves functional values and to continued research on roles of headwater watersheds in larger scale ecosystem functioning. Specific conclusions with implications for watershed management and restoration at Zuni and other semiarid regions include the following:

1. In contrast to previous studies of Southwestern Native American runoff agriculture that assume crops cannot be produced without supplemental moisture from water harvesting, this study shows non-irrigated farming at Zuni to be dependent upon fresh fluvial deposits on active alluvial fans. Farmers concentrate not so much on diverting and spreading runoff water as on protecting alluvial zones from incision and enhancing depositional processes that build desirable agricultural soils. This view of traditional Zuni farming as soil and water conservation is based on input from active farmers and has important implications for current watershed restoration and management issues at Zuni and elsewhere;
2. Upland watershed hillslope and ephemeral stream systems contribute to the productivity and long-term sustainability of rain fed agricultural soils. Forest litter from pinyon, juniper, and oak woodlands is decomposed and mixed with sandy sediments as runoff carries it from source areas on upland slopes through ephemeral stream channels, and deposits it on alluvial fans. Large amounts of fresh organic

matter accumulate on lower watershed slopes. As the material moves through the fluvial system the total mass of organic matter decreases but the concentration of plant available nutrients increases until it peaks in the area of rain fed alluvial fan fields. Frequent, low intensity summer rain showers sort organic materials and facilitate decomposition, moving finer, more decomposed materials down watershed with each minor event. Less frequent intense thunderstorms flush hillslope and fluvial systems, mix organic materials and sediments, and deposit them on the alluvial fans;

3. The relatively infrequent floods play an important role in maintaining and renewing both fertility and water absorbing characteristics of alluvial soils. The fresh, mixed flood deposits are subject to the extreme climate of Zuni, with frequent wetting-drying and freeze-thaw cycles that cause rapid and complete decomposition and release of plant-available nutrients. Therefore, alluvial soils excluded from flooding, either by arroyo cutting or flood control activities, become depleted of organic matter and nutrients. Water absorbing properties also deteriorate as fine, wind- or sheet flow-deposited sediments cover the sandy flood deposits in the absence of flushing floods;
4. Traditional methods for controlling erosion and restoring alluvial soil-building processes proved to be fast, inexpensive, and effective. The methods emphasize construction of multiple brush check dams at key locations in arroyo channels. The structures are built rapidly using materials readily available, are not keyed in to channel beds or banks, and utilize stones only sparingly to compress brush. Over-strengthening with stones or by keying into beds and banks is thought to constrict

intense flows and cause more erosion than it prevents. During relatively frequent low- to moderate-intensity flows the structures dissipate energy and facilitate deposition. During less frequent intense floods many of the structures are transported and redeposited to form debris jams that can significantly impact channel morphology. Structures built with this traditional approach have advantages over more conventional earthen dams and concrete, stone, or log structures because: 1) they can be built rapidly, by hand, and at low cost. This allows more arroyo systems to be treated; 2) they do not cause increased damage and are easy to maintain or rebuild when large flows destroy them; 3) they allow low to moderate flows to reach fields that need moisture; and, 4) the removal of brush and lower branches of pinyon and juniper trees acts as range improvement, increasing grass production and improving sight distances for herders.

Results of the collaborative fieldwork suggest that Zuni farming is an agricultural parallel to adaptive and opportunistic traditional grazing strategies in variable environments. As such, traditional alluvial fan farming constitutes a form of subtle manipulation of fluvial systems as other traditional systems manipulate plant succession. The result is an alternative approach that focuses on fluvial thresholds where modest stimuli, in this case simple brush check dams, lead to significant change, whether to reverse a down cutting tendency or to cause deposition that fills arroyos and moves fan apexes upstream. These are valuable concepts in conservation and restoration of semiarid landscapes. Additional research should continue to explore potential watershed or ecosystem scale effects of this extensive approach and to explore related knowledge of native southwestern and other groups. Combining traditional knowledge of the landscape

with remote sensing technology, for instance, could help to create an index of both erosion vulnerability and restoration potential of ephemeral stream systems that occupy extensive areas of the southwest and other semiarid regions.

At Zuni, traditional people could play a valuable role as the Zuni Tribe prioritizes watershed restoration and conservation and balances this with continued growth and urban development. Traditional ecological knowledge comes from prolonged and intimate contact with complex ecosystems as a means of survival. People who possess traditional Zuni knowledge are becoming fewer and fewer; now is the time to give them a voice in dialogs about environmental issues on the reservation.

The lesson for ecological research that emerges from this work is that collaboration with local people can be more valuable that can be anticipated. Collaboration in the field leads to understanding that may not be achievable by other means. My belief is that this value is not limited to agroecology or to multi-generational, traditional people, but that almost any study that incorporates ecosystem process stands to benefit by collaboration with local people who possess alternative perspectives premised on prolonged and intimate contact with complex ecosystem processes. By failure to include alternative ways of knowing, science not only cheats itself of alternative perspectives not obtainable in any other way, but disrespects local people in ways that discredit science and feed perceptions of a great divide between science and common sense.

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