MODELING EROSION AND TRANSPORT OF DEPLETED URANIUM YUMA PROVING GROUND, ARIZONA

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ABSTRACT

Uranium, chemical symbol U, is a naturally occurring silver-white metal which belongs to the actinide group of elements. Uranium is found as a mixture of three isotopes, ^{238}U, ^{235}U and ^{234}U. Uranium rich in the isotope ^{235}U is preferred for atomic weapons and nuclear reactor fuel. To obtain this isotope, uranium is processed, or enriched, to increase the proportion of ^{235}U. The portion which is deficient in ^{235}U, but rich in ^{238}U, is referred to as depleted uranium or DU. The DU is a workable, malleable metal with a specific gravity of about 19 (about the same as gold), and a melting point of 1132°C. Its high density, relative abundance, and metallic properties have made DU an obvious choice for high energy ballistic projectiles.

The U.S. Army's Yuma Proving Ground (YPG) in southwest Arizona tests DU projectiles. When DU projectiles strike a target or the downrange ground surface, they fragment. Most of the fragments are collected after the test firings, but some are either too small or too dispersed to be easily found. Unfortunately, DU has some undesirable characteristics, it is a radioactive material (alpha particle emitter) and a toxic metal. Therefore, the fragments not found pose a potential environmental hazard at the YPG and to surrounding areas. In order to ascertain what this hazard might be, the U.S. Army has contracted with the Los Alamos National Laboratory (LANL) to study the fate of DU at the YPG. In turn, LANL has contracted with New Mexico State University (NMSU) to investigate water transport of DU during rainfall-runoff events.

Evaluating DU movement with surface water runoff and associated erosion requires an understanding of transport mechanics at the site. In this study, field measurements were taken on site and rainfall/overland flow simulation was used on a 1m x 3m soil box physical model in the laboratory. Nine simulation runs were made on YPG soil containing DU fragments from the impact areas. The nine simulations consisted of three groups of three: rainfall simulation only, overland flow only, and rainfall/overland flow combination.

Infiltration rates in the DU ballistic impact areas at YPG were very close to zero. Larger concentrations of DU were contained in the impact area soil which was retained by the 1 mm and 0.5 mm sieves when grain-size analysis was performed. After all nine simulations were completed, a mass balance of the uranium showed most DU remained in the soil box even under extreme hydraulic conditions, though about 7% (by weight) did exit the box. No DU was found in the suspended sediment samples and this suggests that most transport of DU is restricted to contact or bed-load movement during overland flow. Because the experiments were conducted to simulate extreme rainfall-runoff conditions, the probability of significant transport of DU from land surface appears to be low.

Keywords: Depleted Uranium, Erosion, Flume Study, Overland Flow, Radioactivity, Rainfall Simulation, Sediment Transport

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Conserve New Mexico Water and Soil

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INTRODUCTION

Background

Over the last 50 years the United States has committed itself to developing, testing, and deploying weapons and weapons systems which would strengthen national defense and make the United States a credible adversary in any conflict. The tradeoffs for such a policy have varied in their importance and effects. At one level, the United States conducted hundreds of classified nuclear tests, some of which released radioactive materials to the atmosphere and contaminated areas downwind and the people living there. At another level, the public has heard of countless reports regarding cost overruns of defense projects.

One result of weapons development is the widespread contamination of testing areas. Contamination arises from unspent munitions, explosion residues, and even the wastewater from cleaning weapons. In this report, the residues from non-nuclear, antitank armor piercing ballistics are examined.

This report deals with the unrecovered fragments of spent depleted uranium (DU or ^{238}U) ballistics and their potential transport and fate in an arid environment. Specifically, the study examined the transport of fragmented DU ballistics and associated contaminated soil within a desert watershed.

Depleted uranium has been used extensively in munitions by all branches of the military. Its high specific gravity (19 g/cc), workability, and abundance make it ideal for a high energy ballistic. The high energy and momentum DU projectiles easily pass through most armor plating found in combat vehicles such as tanks and armored personnel carriers. Because of its desirability as a munition, DU has been tested extensively to determine the most appropriate aerodynamic design. The U.S. Department of the Army (Army) has undertaken the testing of DU munitions.

Two Army testing sites for DU are at Aberdeen Proving Ground (APG), Maryland, and Yuma Proving Ground (YPG), Arizona. In 1990, Los Alamos National Laboratory (LANL) undertook a risk assessment study at APG and YPG and examined two primary questions: 1) Is DU transported out of the munitions impact areas and if so by what mechanisms and in what concentrations?; and 2) What are the long-term risks of DU to the ecosystems and the human populations in both areas? In 1992, personnel from the Department of Civil, Agricultural, and Geological Engineering at New Mexico State University (NMSU) were contracted to assist in the study of hydrologic transport mechanisms at YPG. This report presents the results of the investigations conducted by the NMSU study team.

Goal and Objectives

The goal of this investigation conducted by the NMSU team was to evaluate the movement of DU with surface water runoff and associated erosion at the YPG site. The study entailed extensive data collection and observation and used rainfall simulation on site soils in a laboratory environment. Study objectives were to:

1. Determine an appropriate experimental design of the tests to be conducted on the recreated field conditions.

2. Determine erosion and transport characteristics of DU in accordance with the experimental design determined in the first objective.

3. Assist LANL personnel in field surveys and sampling at YPG in support of experimental design and experiments.

4. Coordinate the collection and testing of water and sediment runoff samples from experiments with LANL personnel.

5. Perform relevant statistical and mathematical analysis on the collected data and samples from the experiments and field surveys.

6. Analyze and present the collected data in a final report.

METHODOLOGY

Study Site

The testing of DU munitions at YPG, near Yuma, Arizona, is carried out entirely within the Castle Dome Watershed (Fig. 1). The firing ranges wherein DU projectiles are tested cross areas of gently sloping, dissected, alluvial deposits which are part of a larger, well-braided wash system. Extensive development of desert pavement exists in the interfluve areas. High-intensity rain generates the surface water runoff, and in doing so, transport of DU fragments. The primary areas of interest are the impact areas on the ranges which are located down-range from the various gun positions (GP). Impact areas are so designated because the majority of tested munitions impact, fracture, and disperse within the area.

The most appropriate method of measuring DU transport by surface-water mechanics is through on-site measurements of water flow and DU transport from natural or simulated rainfall-runoff events. This was not practical at the YPG because the area is used heavily for training. Therefore, the study's approach was to gather as much field data as possible at the testing sites during the brief periods of inactivity and then to recreate as close as possible the physical conditions at YPG in a location where experimental rainfall-runoff simulation could be conducted.

Data Collection

Two types of data were collected: field data collected at YPG between April and July 1992 and laboratory data collected between September 1992 and February 1993, in the NMSU hydraulics laboratory. The field data included: a) topographic information, b) hydrologic information and c) soil parameters in and around the impact areas at YPG. Table 1 briefly describes the field sites shown in Figures 1, 2, and 3. The laboratory work consisted of information collected from simulation experiments performed on subsurface soil, desert pavement, DU fragments, and contaminated soil collected from YPG.

Field Data

NMSU personnel made three separate site investigations at YPG. The first trip, made on April 4th and 5th, 1992, concentrated on site inspection. A total of 12 soil grab samples were collected at two different sites, as indicated on Figure 2, designated as E (a channel) and G (impact area in desert pavement formation). Samples were passed through a stack of 10 U.S. standard mesh sieves. In addition, material passing through the #200 sieve was analyzed with a hydrometer test (DAS, 1992) to determine silt and clay percentages. Permeability tests were run on two core samples from site G. Plots of sieve size and percent retained were developed. Channel cross sections were taken at both locations.

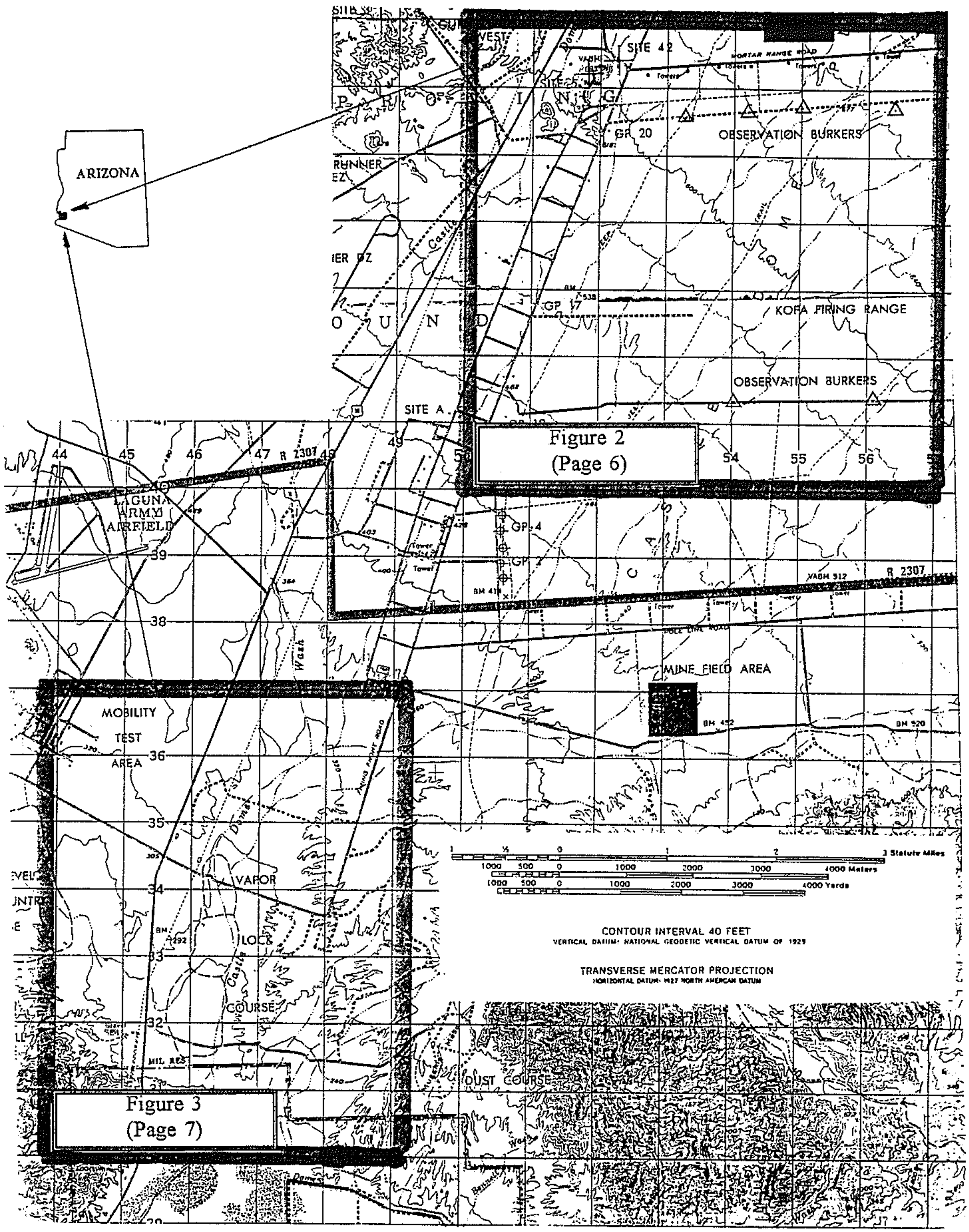

Figure 1. Field Study Locations, Yuma Proving Ground, Arizona

Table 1. Yuma Proving Ground Soil/Sediment Sampling Sites and Study Locations as Shown in Figures 2 and 3.

A. Castle Dome Wash - 15 km Downstream of GP17
B. Castle Dome Wash - 13 km Downstream of GP17
C. Desert Pavement Area Near GP20
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F. Desert Pavement - 3 km Downrange of GP20 (Hill and Berm Area)
G. Desert Pavement - 3 km Downrange of GP20 (Hill and Berm Area)
H. Desert Pavement - 3 km Downrange of GP20 (Hill and Berm Area)
I. Desert Pavement - 3 km Downrange of GP17

A second trip was made May 16 and 17, 1992. At GP (Gun Position) 17 and 20 (Figure 3), detailed physical measurements were taken in and around the impact areas (I and G on Figure 3). These physical measurements included length, width, depth and slope of the impact areas and drainage systems. Possible transport pathways from both wind and water were identified. Three soil grab samples were collected from three different sites and are listed as A, B, and H on Figures 2 and 3. Sieve and hydrometer analyses were performed as described above. Channel cross sections were taken at I, G, and H (Fig. 3).

The final trip was made July 25 and 26, 1992. Infiltration tests, conducted with single-ring infiltrometers, were performed at various sites identified from previous visits. A total of 16 infiltration tests were run at sites A, C, D, and F. Soil samples were taken at each test site and sieve and hydrometer analyses were conducted. Channel cross sections were taken at site A (Fig. 2).

Laboratory Data

The possibility of performing rainfall-runoff simulations on the impact areas was considered. However test firings occur almost daily making on-site simulation impractical. Therefore, a laboratory simulation was devised emulating field conditions in terms of hydrology, surface layout of desert pavement, and DU distribution.

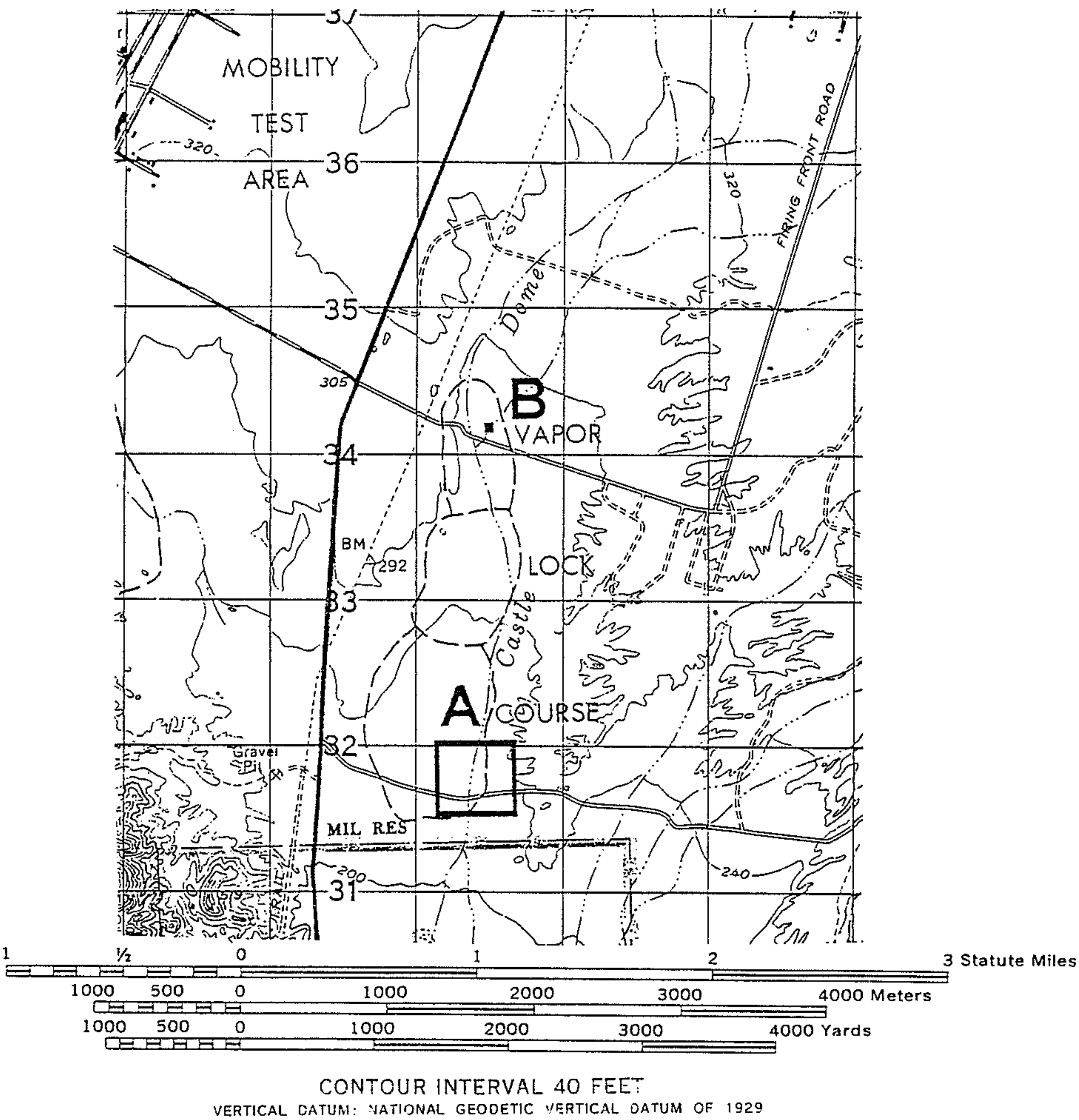

Figure 2. Detail of Sampling Sites, Yuma Proving Ground, Arizona

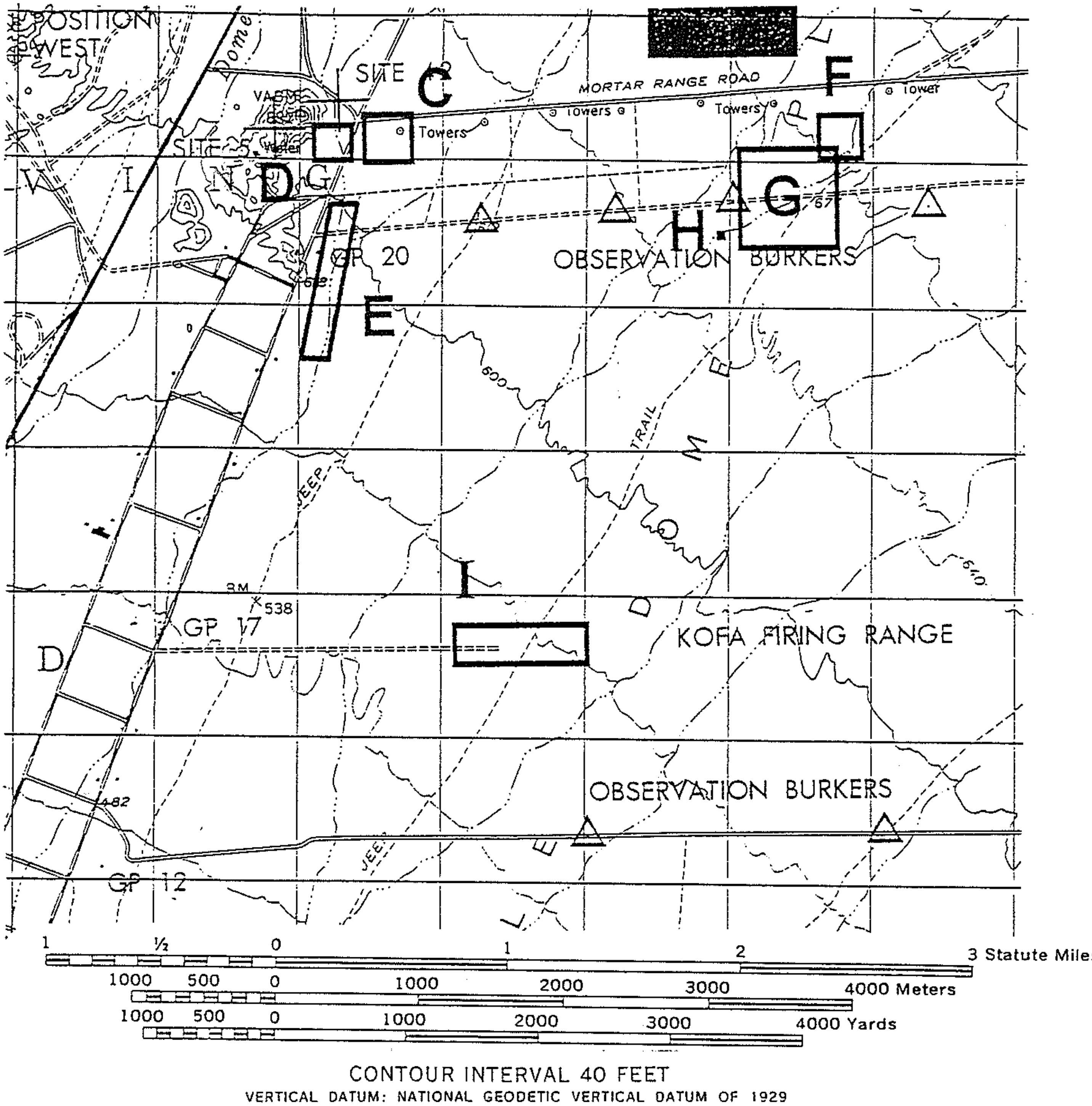

Figure 3. Detail of Sampling Sites, Yuma Proving Ground, Arizona

Runoff surface. At the end of the final field visit in July, 1992, a large soil sample was removed from GP 20 (site C, Figure 3) in the desert pavement formation. This sample was not from a contaminated impact site, but was from the terrain type. The sample consisted of a volume of soil one meter wide, four meters long and ten centimeters deep. Desert pavement was hand picked from each of four 1x1 meter grids comprising the surface of the sample. Each batch of pavement was individually bagged for transport back to the laboratory. The underlying soil was then removed from the plot down to a depth of 10 cm. The sample was transported from YPG to NMSU. In the laboratory, a water-proofed, wooden box was constructed 1m x 3m x 30 cm deep. The soil from YPG was placed in the box to a depth of 10 cm and the desert pavement stones were arranged as close as possible to field appearance. Background radiation activity measurements were made around the area of the soil box using an Eberline, ESP-1 monitor, serial number 007363 provided by LANL. This monitor was used throughout the study to give overall indications of radioactivity.

A grid system with 20 cm x 20 cm squares was constructed of string and light lumber so as to fit inside the soil box such that each node was approximately two centimeters above the surface of the soil. This allowed for radioactivity measurements to be made at consistent X, Y, and Z locations on the soil surface. After the soil from YPG was placed in the box, background radioactivity readings were made at each node on the grid. The collapsible grid was removed during simulations.

Overland flow hydraulics. A principle concern of the study was the possible transport of DU fragments. In comparing field conditions with those in the laboratory, the concept of equivalent stream power was used. Stream power per unit width (e.g. ASCE 1977) can be described as:

$$P_S = \frac{\gamma Q S}{w} \qquad (1)$$

where P_s = Stream power (Newton-m/sec-m^2)
γ = specific wt. of water (Newton/m^3)
Q = flow rate of water stream (m^3/sec)
S = energy slope of flow path (m/m)
w = width of the flow path (m)

The stream power incorporates energy slope, fluid weight, flow depth, and velocity (velocity and depth are directly related to Q) without the need to determine flow depth and surface velocity directly. Because the field-measured infiltration rate into the desert pavement covered YPG soil was found to be very low, the flow rate, Q, can be further described:

$$Q = iLw \qquad (2)$$

where i = applied rainfall intensity (m/hr) [or mm/hr]
L = length of flow path (m)
w = width of flow path (m)

The stream power for the laboratory simulation was equated with that estimated for the YPG site. In equating the stream powers, the following assumptions were used:

-A 100-year return period (1% annual chance of occurence)

-A 1 hour duration design rainfall from the Yuma area of 60 mm (2.35 inches), all of which becomes surface runoff.

-An average distance (length) of 40 m from the impact areas to nearest drainage channel (from field measurements).

-A unit width of 1 meter for the flow path at YPG and in the lab.

-An average slope of 1% along the flow path at YPG.

-A nominal simulator rainfall rate of 75 mm/hr.

-A flow length of 3m for the laboratory simulation (the length of the box containing the YPG soil).

-Desert pavement placed in the simulator box produced the same flow resistance as did the on-site pavement.

It was assumed that the specific weight of rain water between YPG and the laboratory was the same. The only variable that remained to be adjusted, was the slope of the soil box in the laboratory simulation. The necessary slope in the laboratory physical model was calculated to be 10.7% as:

$$S_{lab} = S_{field} \frac{(iL)_{field}}{(iL)_{lab}} = (.01) \frac{(60)(40)}{(75)(3)} = 0.107 \qquad (3)$$

The simulation box was placed at this slope by means of a surveyor's level and rod.

The laboratory and field conditions could also have been equated using measures of applied shear stress, such as total stress or stress against a particle created by the flowing water. However, transport of particles in shallow overland flow is very inefficient without raindrop impact (Ward 1986). Therefore, it was deemed as important to generate high rainfall intensities as it was to produce high flow velocities.

Simulations. Nine simulations were made in the laboratory on the YPG soil consisting of three groups of three. Each run was designated DU1 through DU9. The first three were conducted with rainfall only. The second group of three was conducted by passing the water over a weir at the upper end of the box to simulate overland flow. The last experiments were conducted using the overland flow plus the rainfall simulator in conjunction to produce a worst case scenario of rainfall and overland flow occurring at the same time. Preliminary runs were made using each of the three scenarios in order to season the soil in the box and to optimize data gathering techniques for the actual test runs. Measurements taken during these preliminary runs were used to estimate overland flow resistance for the desert pavement covered YPG soil following the procedures presented by Jorat (1991).

DU Material. Three soil samples containing DU fragments from the impact areas were shipped to NMSU by LANL from YPG. All shipments, handling, and final disposition of the radioactive DU were made in consultation with and under the guidance of the NMSU Health and Safety Office and personnel at LANL. The three soil samples were denoted as low-, medium-, and heavy-DU concentration. The original plan was to perform three different studies on each of the samples. However, once a sample was placed in the simulation box, the box was contaminated for future use. Instead, the three samples were mixed and this mixture was used in the study. The soil mixture's total mass was 6223 grams. A grab sample of the mixed soil was analyzed for grain-size distribution using a stack of 7 U.S. standard mesh sieves: #5 (4.00 mm), #10 (2.00 mm), #18 (1.00 mm), #35 (0.50 mm), #60 (0.25 mm), #120 (0.125 mm), and #270 (0.053 mm). Each fraction was measured for radioactivity with the ESP-1 meter and then sent to LANL for uranium concentration analysis. The remaining soil was then manually spread over the inside of the soil box. Initially, before simulation, readings were taken using the 20 cm x 20 cm grid. Protective clothing and respirators were worn to prevent inhalation of the α-particle emitting DU.

Experimental Runs

Rainfall only. For the first three tests or runs (DU1, DU2, and DU3), experiments were conducted following the approach of Ward and Bolin (1989a,b), with modifications made by Ward (1993). Two elevated, spray down nozzles distributed water evenly over the 1 m x 3 m area at a nominal rate of approximately 75mm/hour. With zero infiltration, this rate would yield a runoff of 3.75 liters per minute from the soil surface. Rainfall rate was checked by collecting the rainfall on an impervious cover. When the desired rate was achieved, the cover was removed and the experiment began.

Runoff was pumped into a Nalgene collection barrel (supplied by LANL) that was placed on balance scales. Every two minutes the weight of the runoff water was measured (in pounds) and converted to volume in liters, using a specific weight of 62.4 pounds per cubic foot. The volume in liters was also read directly from the graduations on the barrel's side as a check. The weight converted volume, however, was used for all calculations. The first three rainfall simulations were designed to last 30 minutes.

Overland flow only. For the next three tests (DU4, DU5, and DU6), overland flow experiments were carried out following the approach of Jorat (1991). A constant head overflow box was placed at the upper end of the soil box such that a continuous flow of water could be applied. The runoff was again pumped into Nalgene collection barrels and the weight noted every two minutes. Weights were checked by direct volume readings from the side of the barrel.

Controlling the flow was more difficult in the overland runs than with the rainfall tests. With the overland flow runs, there was no opportunity to adjust the quantity of flow before applying the water to the soil. Using previous experience, an inflow pressure (measured in the supply hose) was used that would most nearly provide the design flow of 10 liters per minute.

Due to limitations on the total volume of the collection barrel, tests were limited to between 10 and 20 minutes, depending on the actual overland flow rate. However, the total volume of runoff collected was approximately the same for each run.

Combined rainfall and overland flow. Tests DU7, DU8 and DU9 were conducted using rainfall and overland flow simultaneously. Runoff was measured as before, using the weight of the collected runoff and direct volume readings from the collection barrels. Design runoff rates were 15 liters per minute, with 5 liters per minute coming from rainfall and 10 liters per minute coming from overland flow. Tests lasted between 10 and 15 minutes depending on the rate. Again, the controlling factor was total runoff volume.

Post run measurements. Following the nine runs, radioactivity readings were taken at each of the 56 nodes in the grid system. The largest fragment of DU contained in the impact area soil, a 12.6 cm long piece, and was used for relative calibration of the meter. Several times during the collection period, the fragment was measured and the result noted. These readings were compared across the nine simulations and the average was calculated. This average value was labeled as the "standard" and was used to standardize the readings from the ESP-1 meter between each of the runs. The general form of this adjustment was:

$$N_{adj} = N_i \,(FR_{avg}/FT_{avg}) \qquad (4)$$

where:

N_{adj} = Adjusted radioactivity at each node
N_i = Initial, unadjusted radioactivity reading at each node
FR_{avg} = Average radioactivity of calibration fragment for each run
FT_{avg} = Average radioactivity of calibration fragment over all 9 runs

After all experimental runs were completed, the plot was destructively sampled. Soil samples were collected at each grid point. Each sample extended 5 cm into the soil and had a total volume of approximately 98 cubic centimeters and a dry weight of about 157 grams. Each sample was bagged separately and sent to LANL for DU concentration analysis.

Two types of sediment were sampled from the runoff experiments. The first was suspended material which was pumped with the runoff water into the collection barrel. At the end of each run, the water in the barrel was agitated and dip samples were taken. These samples were sent to LANL and analyzed for DU and sediment concentrations. In addition, sediment deposited in or on the water collection tube at the end of the plot was removed, bagged, sent to LANL, and analyzed for DU concentrations. Runoff data from each run were also analyzed to estimate values for overland flow resistance following procedures from Jorat (1991).

RESULTS AND DISCUSSION

Soil Analysis

On-Site Soil

Grain-size analysis graphs for the soil samples collected during the field visits are contained in Appendix A. Site descriptions for each sample are contained in Table 2; and the grain-size analysis information is given in Table 3. As Table 3 indicates, the wash and arroyo samples were exclusively sands with varying degrees of gradation. The soils from the desert pavement areas (where the impact areas are located) were more varied. Just below the surface pavement (large gravel), the soil is consistently a silty sand (10-20 cm). Below this, to a depth of about 50 cm, more clay is present. At a depth of 50 cm, more sand appears to be included in the soil, thus the soil is classified as sandy silt. This is consistent with theories on desert pavement formation (McFadden et al., 1987).

Table 4 shows the results of the two laboratory permeability tests performed on soils removed from site G. The laboratory measured permeability is quite low. This result is supported by the infiltration tests (Table 5). Ring-infiltration rates near the surface of the pavement-covered soils averaged 17 mm per hour, which was just slightly above the measured evaporation rate of 10 mm per hour. The low ring-infiltration rates are such that the rainfall infiltration rates would be near zero. Infiltration rate increased by a factor of 10 at a depth of 50 mm below the surface.

Contaminated Soil

Grain-size analysis of the sample taken from the impact area (contaminated) soil is shown in Table 6 and Figure 4. Also contained in Table 6 are the radioactivity counts and DU concentrations. Larger concentrations of DU were contained in the soil retained by the 1 mm and 0.5 mm sieves. A high correlation exists between the radioactivity readings and the measured DU concentrations.

The correlation between counts measured using the ESP-1 meter and the DU concentrations as supplied by LANL were investigated further. The concentration term of micrograms U per gram of soil can be expressed as a percentage of U per soil weight if the concentration is divided by 10,000. Therefore, 42,243 µg-U/g-soil is equal to 4.22% U by weight of the soil. The counts and concentration values were combined with the same type of data measured in the deposited sediment from the simulation runs. It was found that a linear relationship of:

$$\%U = -0.045851 + 0.086103\ CNT \qquad (5)$$

where r = 0.94

n = 15

%U = percent of U in the dry soil by weight

CNT = radioactivity counts (1000's/min)

r = linear correlation coefficient and

n = number of observations

Table 2. Description of Soil Sampling Sites

A. Castle Dome Wash - 15 km Downstream of GP17

1. Surface Sample #1
2. Surface Sample #2
3. Surface Sample #3
4. Surface Sample #4
5. Surface Sample #5 (Main Channel)
6. 1.5 m Below Surface

B. Castle Dome Wash - 13 km Downstream GP17

Magazine Road - Surface Sample

C. Desert Pavement Area Near GP20

1. Sample #1, Surface Gravel Removed
2. Sample #1, Surface Gravel
3. Sample #2, Surface Gravel Removed
4. Sample #2, Surface Gravel
5. Sample #3, 50 cm Below Surface
6. Sample #4, Surface Gravel Removed
7. Sample #5, 50 cm Below Surface
8. Sample #6, Surface Sample with Gravel Included

D. Arroyo Near GP20

1. Sample #1
2. Sample #2
3. Sample #3

E. Arroyo Near GP20

1. Sample #4
2. Sample #5
3. Sample #6
4. Sample #7

F. Desert Pavement - 3 km Downrange of GP20 (Hill and Berm Area)

1. Surface Sample #1 (top 10 cm), with Gravel Included
2. Surface Sample #2 (top 10 cm), with Gravel Included

G. Desert Pavement - 3 km Downrange of GP20 (Hill and Berm Area)

1. Surface Sample #1, with Gravel Included
2. Soil Below Gravel Layer Sample #1 (to 10 cm)
3. 10-20 cm Below Surface
4. Small Arroyo Sample #1
5. Small Arroyo Sample #2
6. Small Arroyo Sample #3
7. Surface Sample #2, with Gravel Included
8. Soil Below Gravel Layer Sample #2 (to 10 cm)

H. Desert Pavement - 3 km Downrange of GP20 (Hill and Berm Area)

Main Arroyo Sample

Table 3. Soil Grain-Size Analysis Yuma Proving Ground, Arizona

Sample	D_{10}	D_{16}	D_{50}	D_{84}	D_{90}	$\sqrt{\frac{D_{84}}{D_{16}}}$	C_u	C_c	Color and USCS Classification
A1	0.200	0.250	0.980	5.30	7.40	4.60	0.61	8.60	Dark grey & brown SP
A2	0.200	0.250	0.940	6.00	8.10	6.90	0.59	9.00	Dark grey & brown SP
A3	0.610	0.560	1.250	4.20	5.60	2.79	0.94	6.10	Dark grey & brown SP
A4	0.220	0.260	0.770	2.80	4.00	3.28	0.89	4.30	Dark grey & brown SP
A5	0.560	0.670	2.300	6.00	7.80	2.99	5.20	0.52	Yellow & black SP
A6	0.170	0.220	0.700	3.00	4.30	3.69	0.78	5.10	Dark grey & brown SP
B	0.270	0.320	1.800	7.20	9.40	4.79	10.4	0.62	Yellow & black SP
C1*	0.010	0.025	0.220	2.60	4.60	10.20	na	na	Yellow SM
C2	6.400	6.900	9.700	16.00	18.00	1.52	0.83	1.90	Black GP
C3*	0.003	0.010	0.120	4.75	7.20	22.36	na	na	Yellow SM
C4	7.300	8.500	16.000	30.00	36.00	1.88	1.29	2.50	Black GP
C5*	0.086	0.017	0.140	1.70	4.00	10.00	na	na	Yellow SM
C6*	0.002	0.043	0.069	2.10	4.75	6.99	na	na	Yellow ML
C7*	0.010	0.025	0.170	2.90	5.50	10.77	na	na	Yellow ML
C8	0.210	0.430	5.800	20.00	250	6.82	2.32	39.0	Yellow & black GW
D1	0.300	0.520	1.600	5.30	7.10	3.19	1.03	8.00	Grey & brown SW
D2	0.650	0.900	2.700	7.70	9.30	2.92	0.91	5.80	Grey & brown SP
D3	0.620	0.850	3.300	13.00	21.00	3.91	0.62	8.20	Grey & brown SP
E1	0.400	0.570	4.100	22.00	28.00	6.21	15.80	0.57	Brown SP
E2	0.600	0.800	3.700	9.00	11.00	3.35	8.00	6.75	Brown SP
E3	0.770	1.300	6.100	13.00	15.50	3.16	9.70	1.67	Brown GW
E4*	0.020	0.028	0.087	5.60	7.30	14.68	na	na	Light-yellow SM
F1*	0.002	0.003	0.032	1.00	8.50	18.57	na	na	Yellow CL-ML
F2*	0.002	0.004	0.035	4.75	15.00	36.32	na	na	Yellow CL-ML
G1	7.200	9.400	17.000	26.00	32.50	1.66	2.60	1.14	Black-grey GP
G2*	0.002	0.005	0.033	0.15	0.36	5.77	na	na	Yellow CL-ML
G3*	0.002	0.006	0.062	4.00	8.30	26.73	na	na	Yellow SC
G4*	0.049	0.080	2.000	9.80	1.600	11.07	na	na	Yellow SM
G5*	0.073	0.095	1.300	9.00	13.00	96.74	35.60	0.84	Brown SP
G6	0.330	0.670	8.200	28.00	36.00	6.46	40.90	1.63	Brown GW
G7	13.000	15.000	25.000	41.00	44.00	1.65	2.10	1.01	Black-grey GP
G8*	0.030	0.076	0.408	31.00	38.0	20.20	na	na	Yellow SM
H	0.30	0.410	3.000	10.00	17.50	4.94	15.00	0.49	Yellow & black SP

NOTE:

D_{10}, D_{16}, D_{50}, D_{84}, D_{90} are the diameters corresponding to percents finer of 10%, 16%, 50%, 84%, 90%, respectively.
C_u is uniformity coefficient of soil.
C_c is coefficient of gradation of soil.
* Sieve and hydrometer analysis
Soil classification system: United Soil Classification System (USCS)
SP - Poorly graded sand (A3, A4, A6)
SP - Poorly graded sand with gravel (A1, A2, A5, D2, D3, E1,E2, H, G5, B)
SW - Well-graded sand with gravel (D1)
SM - Silty sand (C1, C5)
SM - Silty sand with gravel (C3, E4, G4, G8)
GP - Poorly graded gravel (C2, C4, G1, G7)
GW - Well-graded with sand (C8, E3, G6)
SC - Clayey sand with gravel (G3)
ML - Sandy silt (C7, C6)
CL-ML - Sandy silty clay (F1, G2)
CL-ML - Sandy silty clay with gravel (F2)

Table 4. Coefficient Of Permeability Test

Location of sampling	Dry unit weight* (kPa)	Void ratio**	Coeff. of permeability*** (cm/sec)
Site G, desert pavement surface	14.7	0.787	2.5×10^{-6}
Site G, desert pavement surface	15.4	0.787	1.1×10^{-6}

Note: * Dry unit weight γ_d = (Dry weight of soil W_s)/(Volume of the soil V)
** Void ratio $e = G_s\rho_w/\rho_d - \rho_w$
where G_s is specific gravity, assume $G_s = 2.68$ for silt.
ρ_w is density of water, 1 g/cm^3.
ρ_d is density of soil, $\rho_d = \gamma_d/g$,
$g = 9.81$ m/sec^2, g is acceleration of gravity.
*** Coefficient of permeability was determined by falling head permeability test.

This equation can be used to estimate the DU concentration in a sample based on the number of counts per minute. The concentration of the > 4.00 mm fraction in Table 6 was calculated in this way. A comparison of concentrations and counts is shown in Figure 5.

Runoff and Plot Data

Appendix B contains the raw runoff data from each of the simulation experiments. Table 7 shows values of different variables associated with each of the runs. The first three runs were rainfall only and were held fairly constant for rainfall rate and duration (total runoff). The next three runs (DU4, DU5, and DU6) were overland flow only. The last three runs consisted of combined rainfall and overland flow.

The data in Table 7 show several results (see appendix B for more detailed information including suspended sediment yields). First, overland flow alone is not efficient at moving sediment from the plot. This can be seen by the lower deposit weights for run numbers DU4 through DU6. These runs had higher runoff rates than the rainfall-only and equivalent rates to the combined rainfall and overland flow. Second the loss of DU from the plot it apparent by the concentration of DU in the deposits and the decrease in the grid-based radioactivity counts with time (accumulating flow volume or runoff energy). Note that the grid-based activities (measured with the ESP-1 meter, see Plate 1, Appendix C) do not correspond exactly to U concentrations measured in the soil by ion chomotography because ESP-1 measurements do not correct for

Table 5. Results of Ring Infiltration Tests at Yuma Proving Grounds, Arizona, July 1992

Location	Description	Infililtration Rate mm/hr	Remarks
Site A			
Test 1	Arroyo (surface)	705.0	
Test 2	Arroyo (surface)	709.0	
Test 3	Arroyo (surface)	2013.0	
Test 4	Arroyo (surface)	950.0	
Test 5	Arroyo (1.5m below surface)	574.0	Tighter soil
Site C			
Test 1	Desert Pavement Site GP20 (Undisturbed Surface)	24.0	Evaporation rate* 10mm/hr
Test 2	As above	9.0	As above
Test 3	Desert Pavement Site GP20 (50cm below surface)	151.0	Very tight clay
Test 4	Same as Site C Test 1	16.0	Evaporation rate 10mm/hr
Test 5	Desert Pavement Site GP20 (50cm below surface)	165.0	
Test 6	Desert Pavement Site GP20 (Undisturbed Surface)	326.0	Much more sand/gravel than other pavement sites
Site D			
Test 1	Arroyo near GP20	3474.0	
Test 2	Arroyo near GP20	9189.0	Gravelly
Test 3	Arroyo near GP20	2115.0	
Site F			
Test 1	Hill/Berm Area Desert Pavement Site	20.3	Evaporation rate 10-15 mm/hr
Test 2	As above	14.3	as above

*Evaporation rate measured in soil tin placed next to ring infiltrometer.

Table 6. Yuma Proving Ground Area Soil: Grain-Size Analysis, Radioactivity and U concentration.

Sieve (#)	Opening (mm)	Retained (%)	Radioactivity[1] (counts/min)	U Concentration[2] (μg-U/g-soil)
5	4.00	25.8	28,800	24,300(est)
10	2.00	10.5	56,700	42,243
18	1.00	10.6	57,400	60,481
35	.500	10.6	60,100	59,225
60	.250	8.5	52,000	31,743
120	.125	9.3	39,800	30,817
270	.053	16.1	22,400	18,144
pan	-	8.0	20,200	17,225

[1]As measured using a Eberline ESP-1 meter the total sample weight was 558g.
[2]As measured by ion chromatography at LANL.

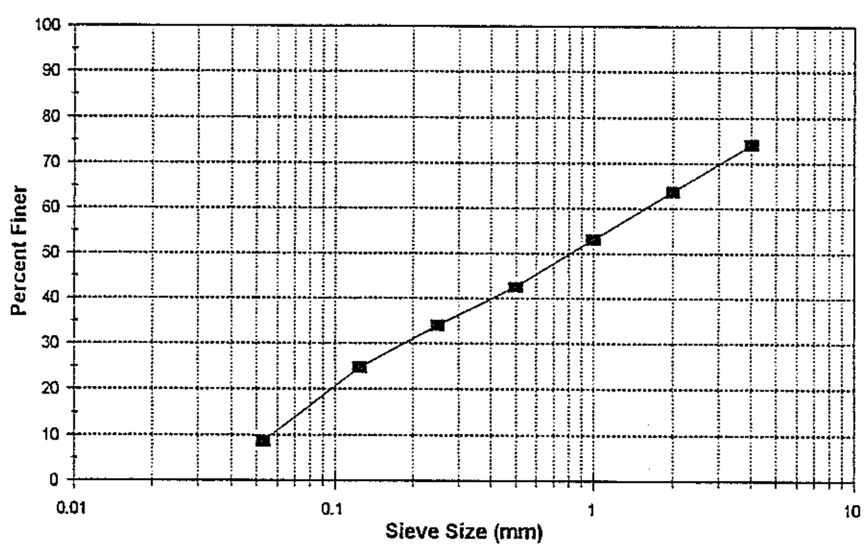

Figure 4. Yuma Proving Ground Impact Area Soil - Grab Sample Grain-Size Analysis

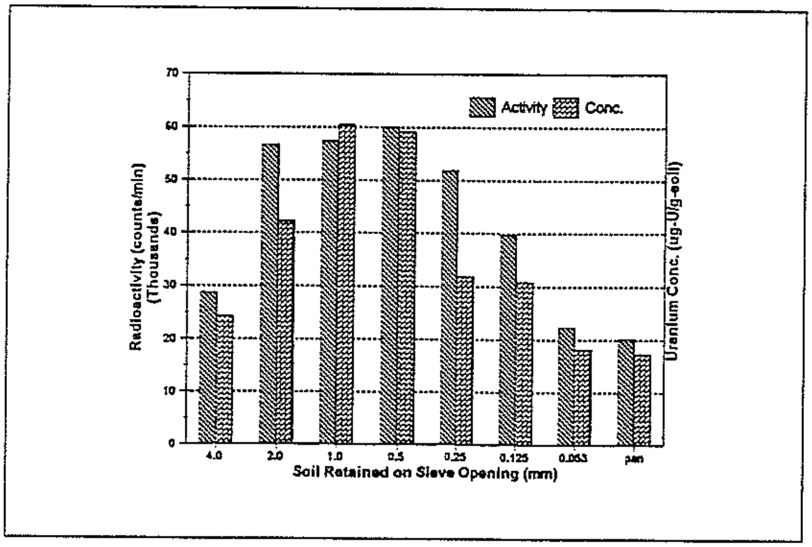

Figure 5. Uranium Activity/Concentration and Sieve Size in Yuma Proving Ground Impact Area Soil.

absorption of radiation by the soil in which DU is mixed. DU on the soil surface provides a different signal to the ESP-1 than does DU mixed in the soil.

Figure 6 shows the cumulative fractional gains or losses in U or counts, respectively, across the sequence of the experimental runs. This figure indicates that the finer materials left the plot early in the sequence which can be seen in Plates 2 and 3. By the time the overland flow only experimental runs commenced (Plate 4), the DU was beginning to reach a stable configuration (e.g. Plate 5) with very little exiting the box (Plate 6). The combined rainfall and overland flow added sufficient transport energy to move the rest of the deposited DU that was to leave the box.

Figures 7, 8, 9, and 10 illustrate the redistribution of the DU contaminated soil during the experimental runs (See also Appendix E). In the figures, the flow is from left to right. Position (0.2, 0.2) corresponds to grid point D1 in Table 8. Examination of figure 7 through 10 in sequence shows the effect of water transport on the movement and redistribution of DU on the plot. Note again that the counts as used in these figures are indicative of the DU on the soil surface and not necessarily mixed in the soil.

After run number DU9, soil samples were removed at each grid point and the U concentration was measured at LANL using ion chromotography. Sampling results are presented in Table 8 and illustrated in Figure 11. There is an unusually high concentration at grid location B9 which is associated with the DU "fragment" The fragment was used for calibration and as a marker on the plot. Recall that the DU fragment was not incorporated in the grid counts because it overshadowed all other values and did not move significantly with the flowing water. The average concentration of DU in the remaining 55 soil samples [(4x14)-1] was 821.55 μg U per gram of soil (or 0.08% by weight). Mass balance computations on the DU were conducted as illustrated in Table 9. The closure is extremely good given the heterogenous distribution of soil and DU fragments in the box and in the transported sediments. A 95% confidence interval

Table 7. Flow Data and Plot Radioactivity.

Run #	Out flow rate (l/m)	Runoff volume (liters)	Deposits (g)	Counts/min in deposits	%U in deposit by weight	Average counts on plot*
Initially	-	-	-	-	-	12472
DU1	4.3	122.7	198.92	10000	0.96	12195
DU2	4.3	121.6	161.98	13000	1.54	7749
DU3	4.2	129.5	174.85	15000	1.27	4859
DU4	14.7	218.0	34.62	26400	2.07	5872
DU5	8.1	154.5	none	none	none	4675
DU6	17.0	218.2	26.29	20000	1.40	4598
DU7	12.6	185.1	135.36	10000	1.18	4221
DU8	16.5	203.5	294.00	12500	0.71	3516
DU9	17.4	257.2	246.74	15500	0.91	2932
Total	-	1610.3	1272.96	-	-	-

*This is the average of all the grid point radioactivity measurements on the test plot in units of counts per 30 sec.
Runs DU1 through DU3 were rainfall only
Runs DU4 through DU6 were overland flow only
Runs DU7 through DU9 were a combination of rainfall and overland flow

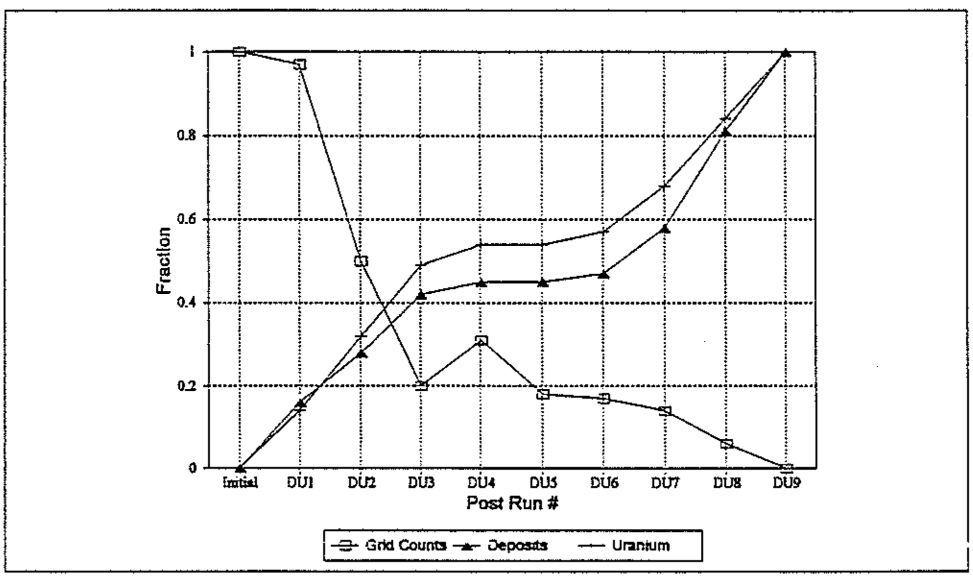

Figure 6. Fractional gain in U and sediment deposits from plot compared to fractional reduction in average counts on the plot. Counts are adjusted so that the fractional range is 0 to 1.

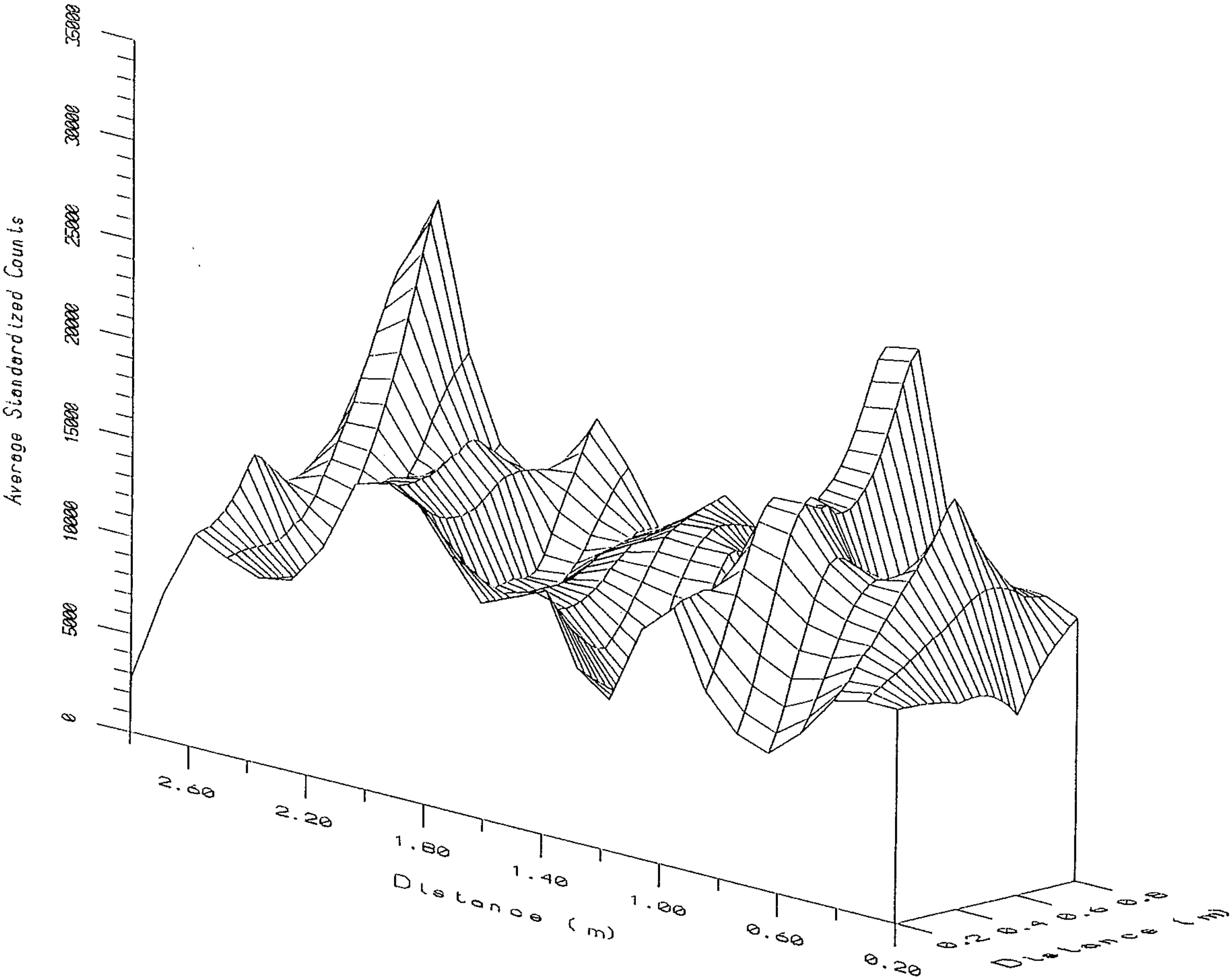

Figure 7. Radioactivity on plot surface before run # DU1

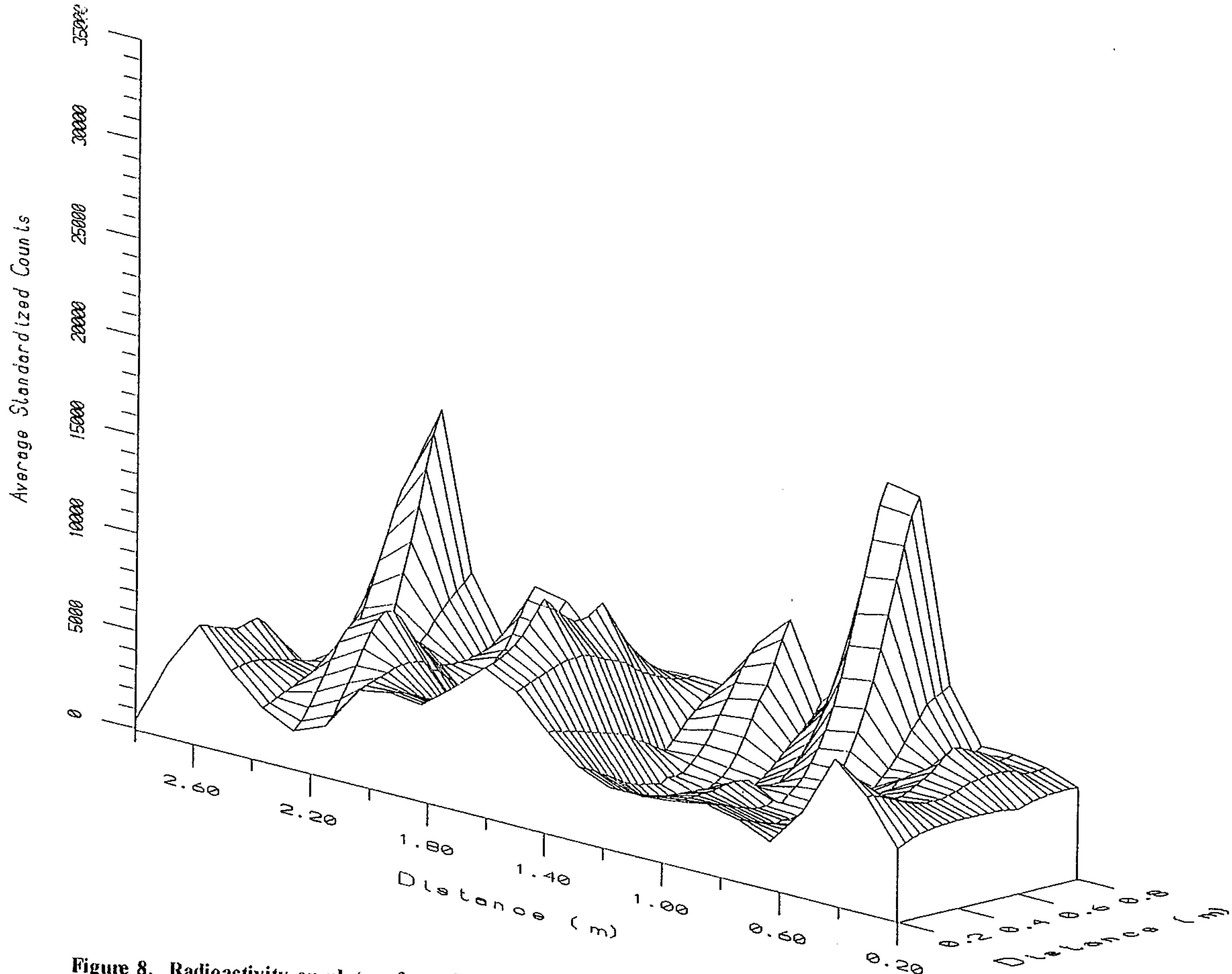

Figure 8. Radioactivity on plot surface after run # DU3

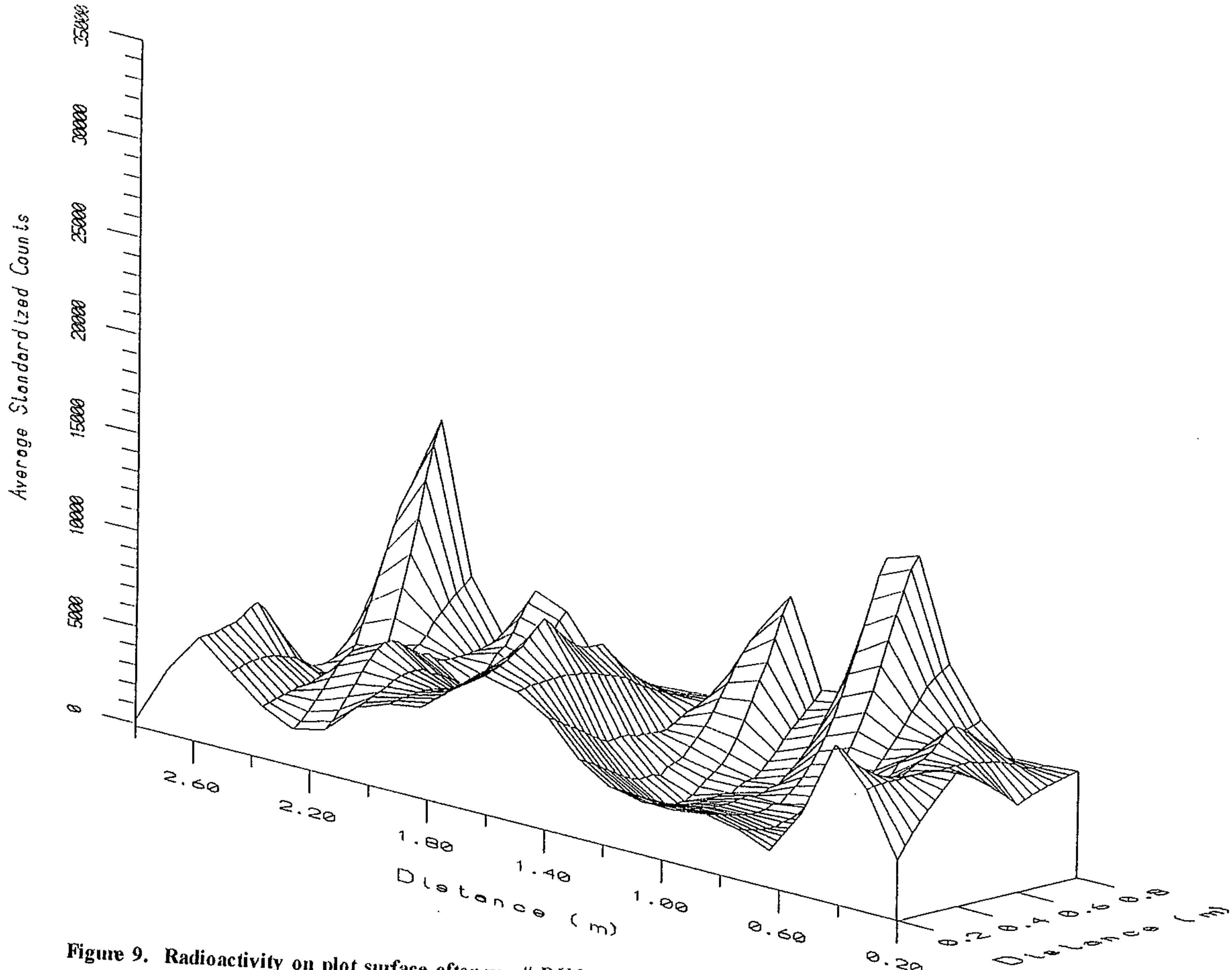

Figure 9. Radioactivity on plot surface after run # DU6

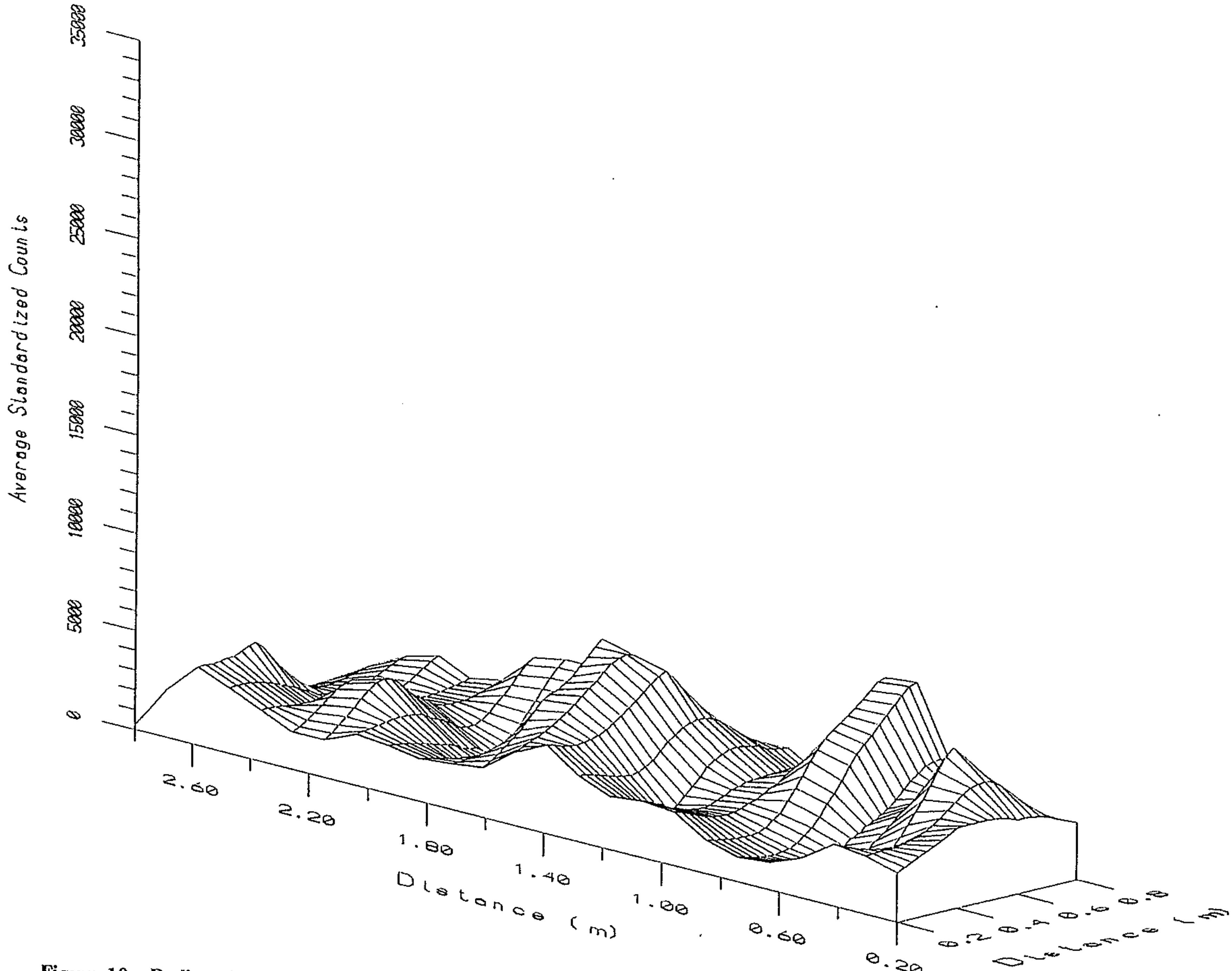

Figure 10. Radioactivity on plot surface after run # DU9

for the amount of DU remaining in the soil was calculated. Because of the at-point variability in the DU concentrations, the confidence interval was two orders of magnitude and is not realistic when compared to mass of DU in the mixed soil. Appendix E contains the information associated with calculating overland flow resistance (Manning's 'n') and a graphical representation of the overland flow resistance for each run.

Table 8. Average Concentration in Plot Soil after Run DU9

Plot Coordinates	Average U Concentration[1] (µg-U/g-soil)			
	A	B	C	D
1	428.45	93.73	687.28	287.97
2	2458.60	355.59	225.68	212.45
3	874.65	385.16	332.53	458.66
4	1288.01	410.38	836.50	4797.64
5	736.75	350.24	169.86	1669.05
6	561.88	309.11	325.88	190.32[2]
7	396.92	494.04	353.72	438.27
8	240.27	656.73	3580.22	1110.18
9	1498.89	14780.67	679.44	4935.66
10	533.06	714.41	387.11	1036.72
11	1210.85	998.96	308.40	695.16
12	758.04	1710.49	101.44[2]	1139.43
13	788.87	459.48	200.21	574.43
14	-[3]	-[3]	-[3]	248.94

[1] Measurements based on soil dried 110 °C for 24 hours.
[2] Only one measurements, all others are average of two measurements.
[3] Below detection limit of 0.05.

Discussion

The closure of the mass balance indicates that most of the DU remained in the box even under extreme hydraulic conditions. However, about 7% did exit the box. The grid count 3-D projections shown in Appendix D indicate that there was a loss of DU from the entire box area and not from the portion nearest the collection pipe. This general transport is confirmed by measurement of DU particle movements after each run and after photos before and after each run shown in plates 1 through 6. It was surprising that no DU was found in the suspended sediment samples. This strongly suggests that most transport of DU could be restricted to contact or bed load movement during overland flow. Channel flow, because of its higher energy, would be more efficient at moving the DU particles supplied from the impact area surface. However, because the experiments were conducted to simulate extreme conditions, the probability of significant overland flow transport from the surface of the impact area appears to be low.

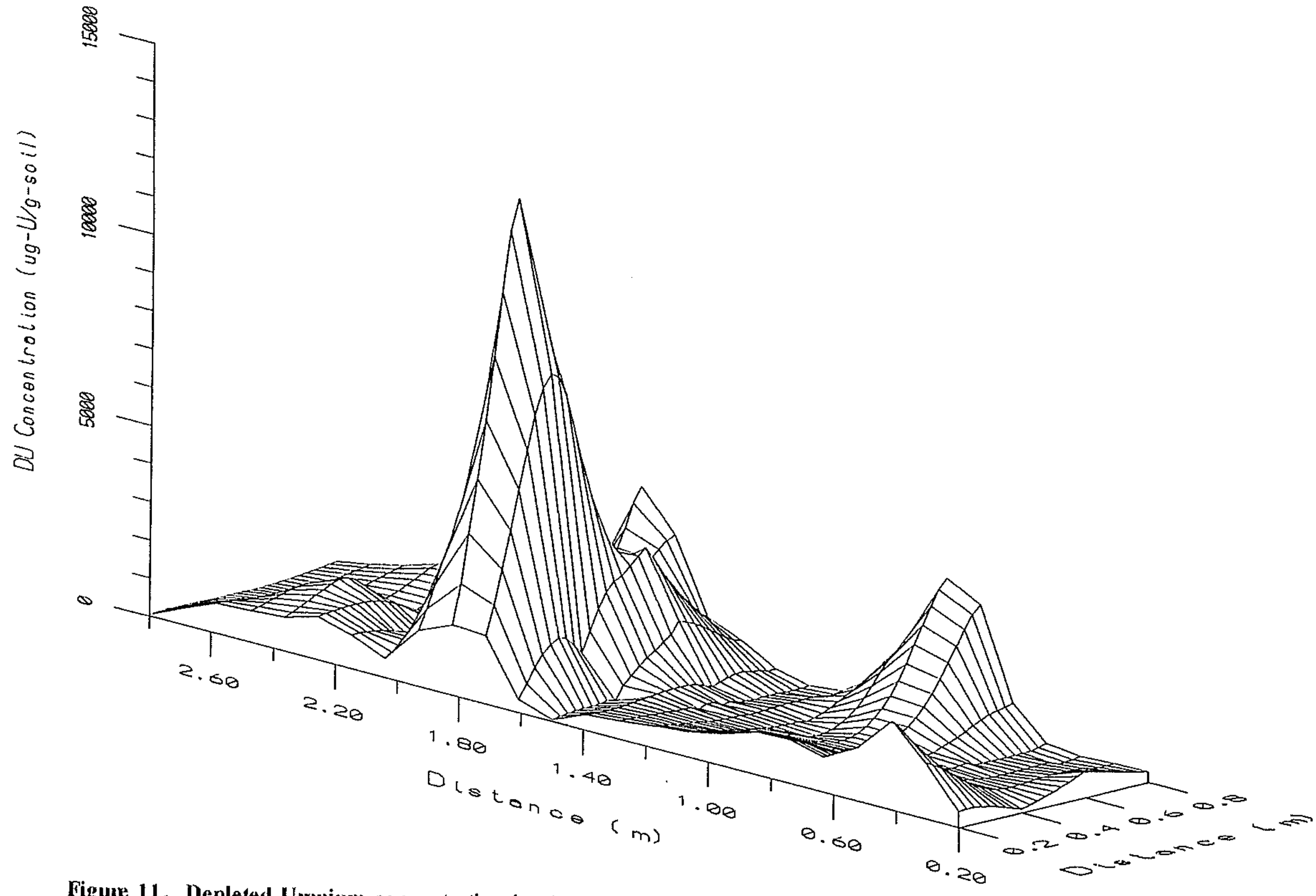

Figure 11. Depleted Uranium concentration in plot soil after Run DU9.

Table 9. DU Mass Balance Computations for Applied Soil and Collected Samples

6223 g	mixed soil and DU
-300 g	DU fragment
5923 g	available for transport
5923 g	
x0.0333	grams DU/grams mixed soil (from Table 5)
197 g	DU in Box (not counting fragment)
197 g	
-14 g	DU in deposits (13.65 g = 14 g)
183 g	
183 g	
- 0 g	DU in suspended sediment (No DU detect per LANL)
183 g	
100 cm	
x 300 cm	
x 5 cm	
150,000 cm^3	volume of soil in box from which samples were collected
150,000 cm^3	
x 1.54 g/ cm^3	unit weight of soil in box
231,000 g	weight of sample in box
231,000 g	
x 0.00082155	g-U/g-soil
190 g	DU is soil layer
183 g	
- 190 g	
-7 g	(7/197) X 100% = 3.55%

CONCLUSIONS

Depleted uranium can be transported by overland flow. Transport is most effective in the presence of raindrop impact. In the experiments conducted during this study about 7% by weight of DU was removed from a test plot box under the influence of rainfall, overland flow, and combined rainfall and overland flow. The conditions which were simulated were extreme and represent those arising from low frequency, high magnitude events. Although DU was found in the sediment deposits, it was not found in suspended sediment samples. Study results imply that DU is fairly immobile with respect to water erosion on the land surface. Although the study was designed to accurately simulate rainfall-runoff conditions as they might exist on theYPG, field verification of the laboratory observations is desirable. It is suggested that on-site simulated rainfall-runoff experiments be designed for and conducted at YPG which examine a variety of surface and slope conditions. It is also recognized that if DU particles are in direct contact with rills, gullies, or channels, there may be sufficient flow energy to transport the particles. Therefore, another important follow up study would be to investigate DU transport in simulated arroyos/channels wherein the flow depths and velocity were much larger than those found in overland flow. Results of that type of investigation would then complement the findings of this study regarding rainfall-runoff transport.

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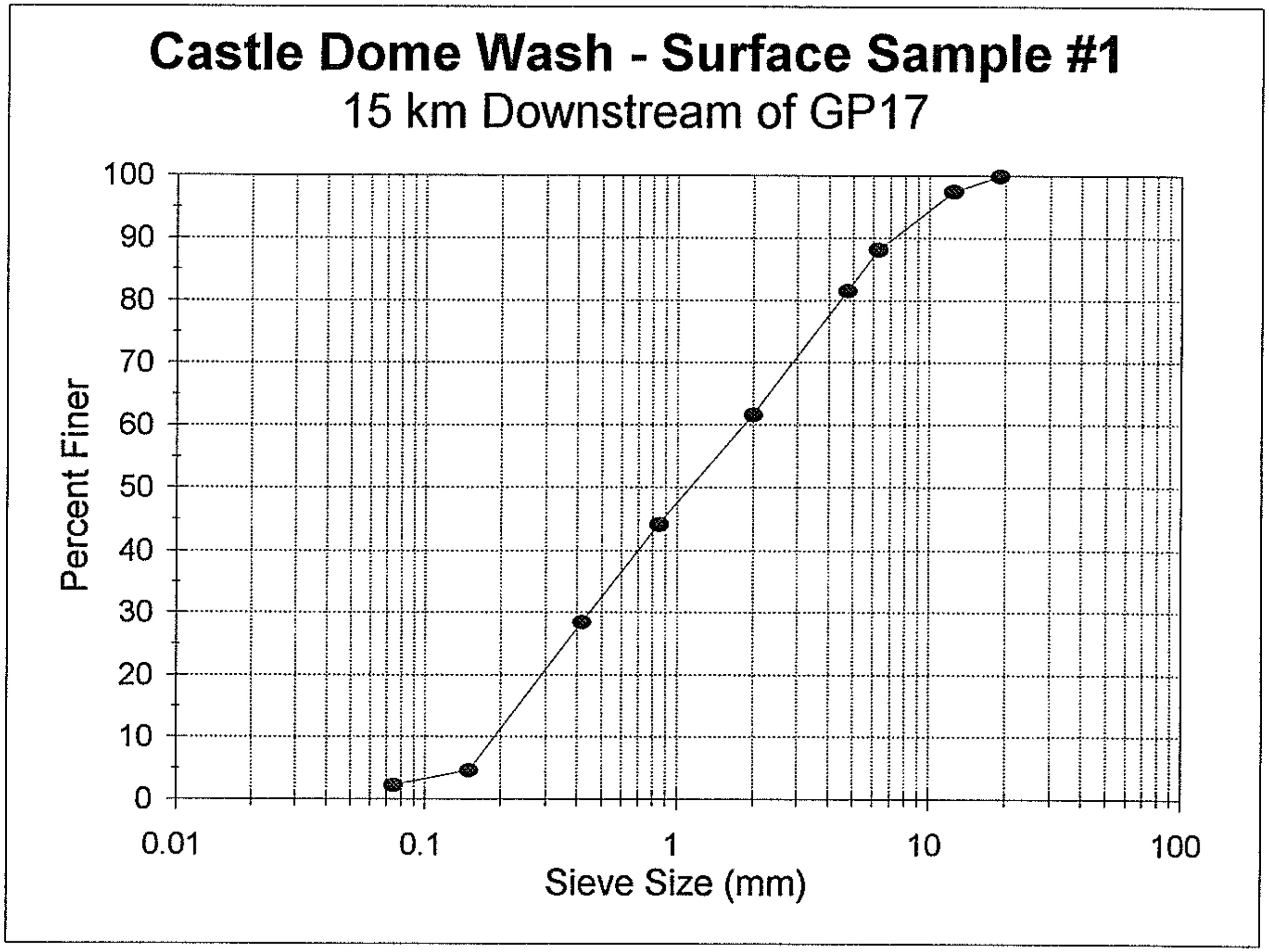
APPENDICES

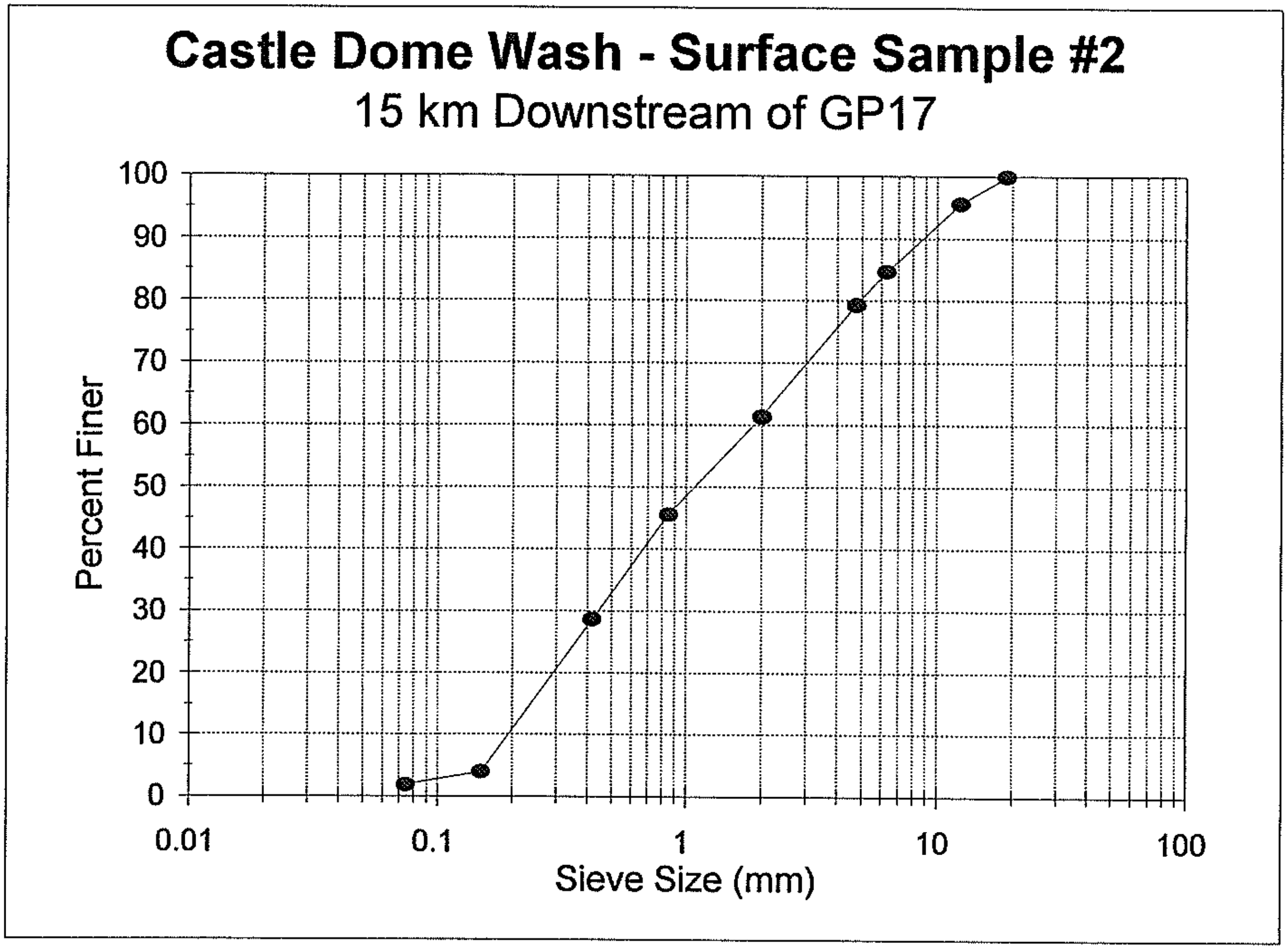
Appendix A

Grain-size Analysis Plots

Sieve Size (mm)	Percent Finer (%)
19.000	100.0
12.500	97.5
6.300	88.2
4.750	81.6
2.000	61.7
0.850	44.2
0.420	28.5
0.150	4.7
0.075	2.3



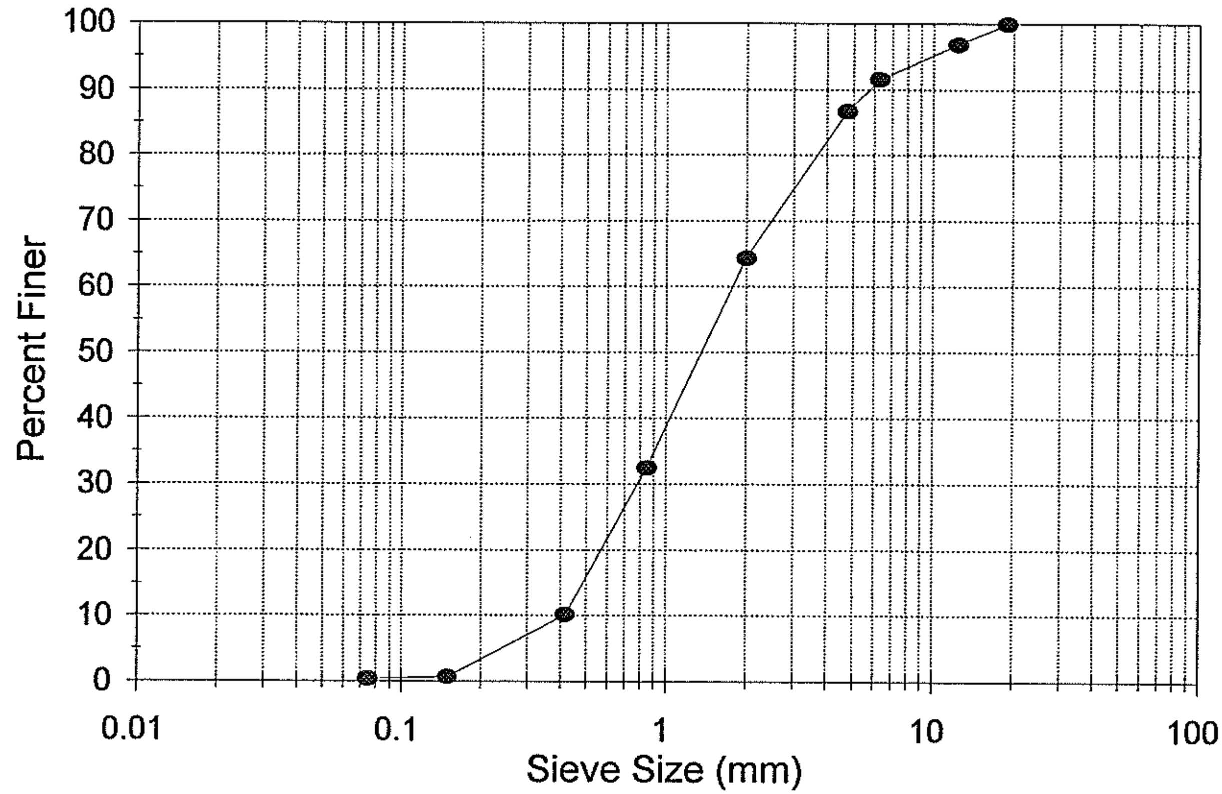
Sieve Size (mm)	Percent Finer (%)
19.000	100.0
12.500	95.6
6.300	84.7
4.750	79.4
2.000	61.4
0.850	45.6
0.420	28.7
0.150	4.0
0.075	1.9



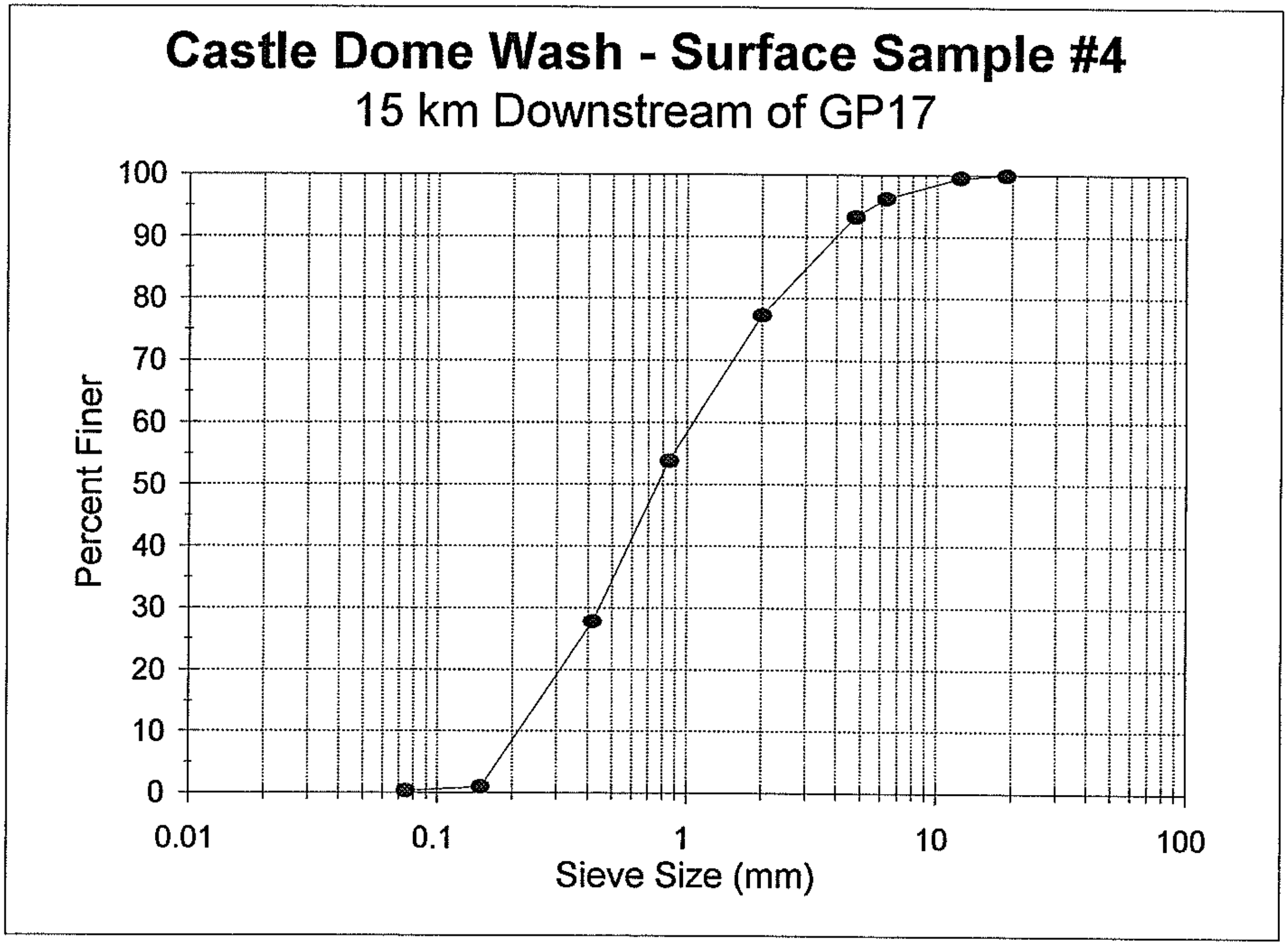
Sieve Size (mm)	Percent Finer (%)
19.000	100.0
12.500	96.9
6.300	91.6
4.750	86.7
2.000	64.4
0.850	32.5
0.420	10.2
0.150	0.7
0.075	0.4

Castle Dome Wash - Surface Sample #3

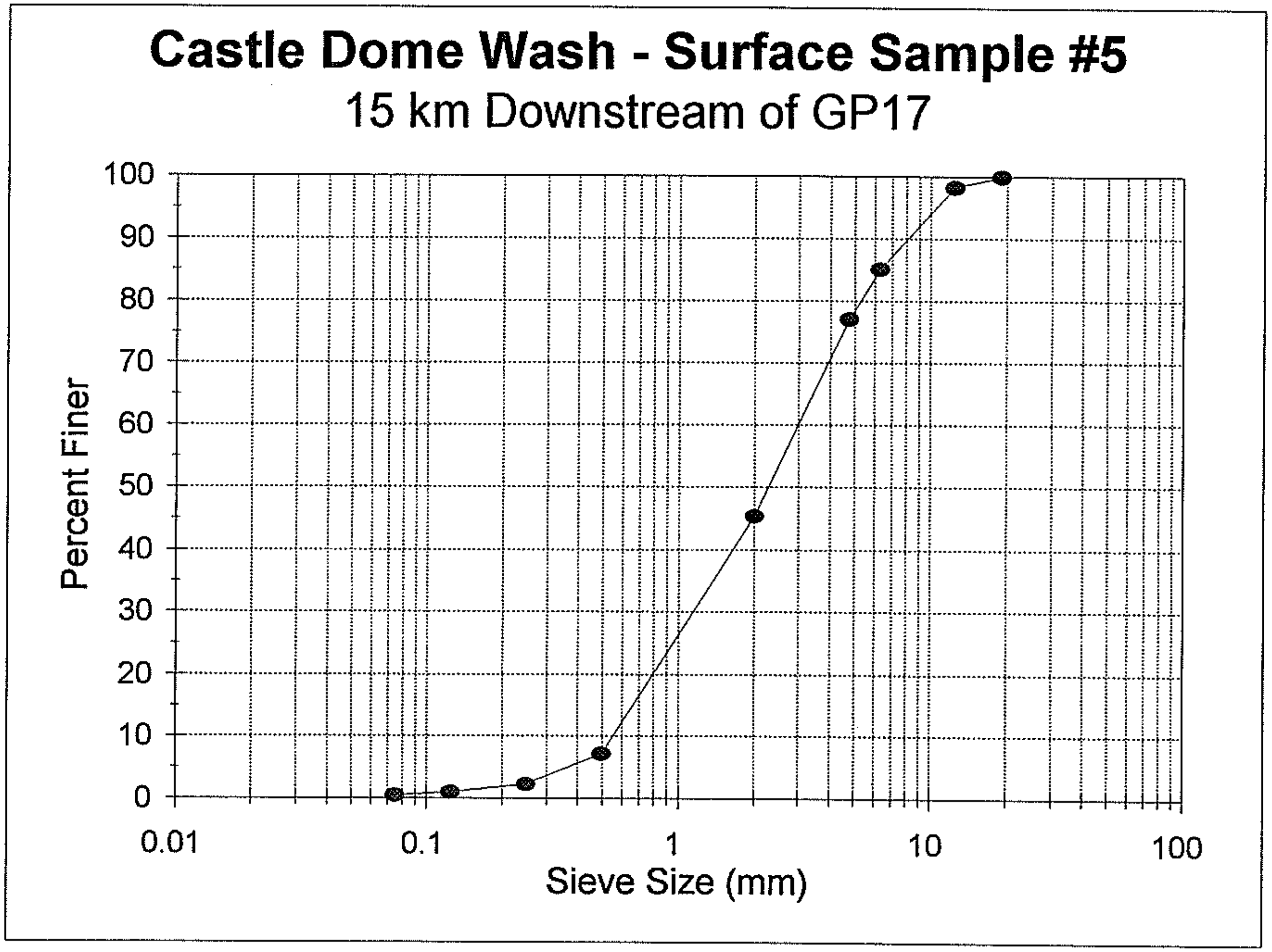
15 km Downstream of GP17



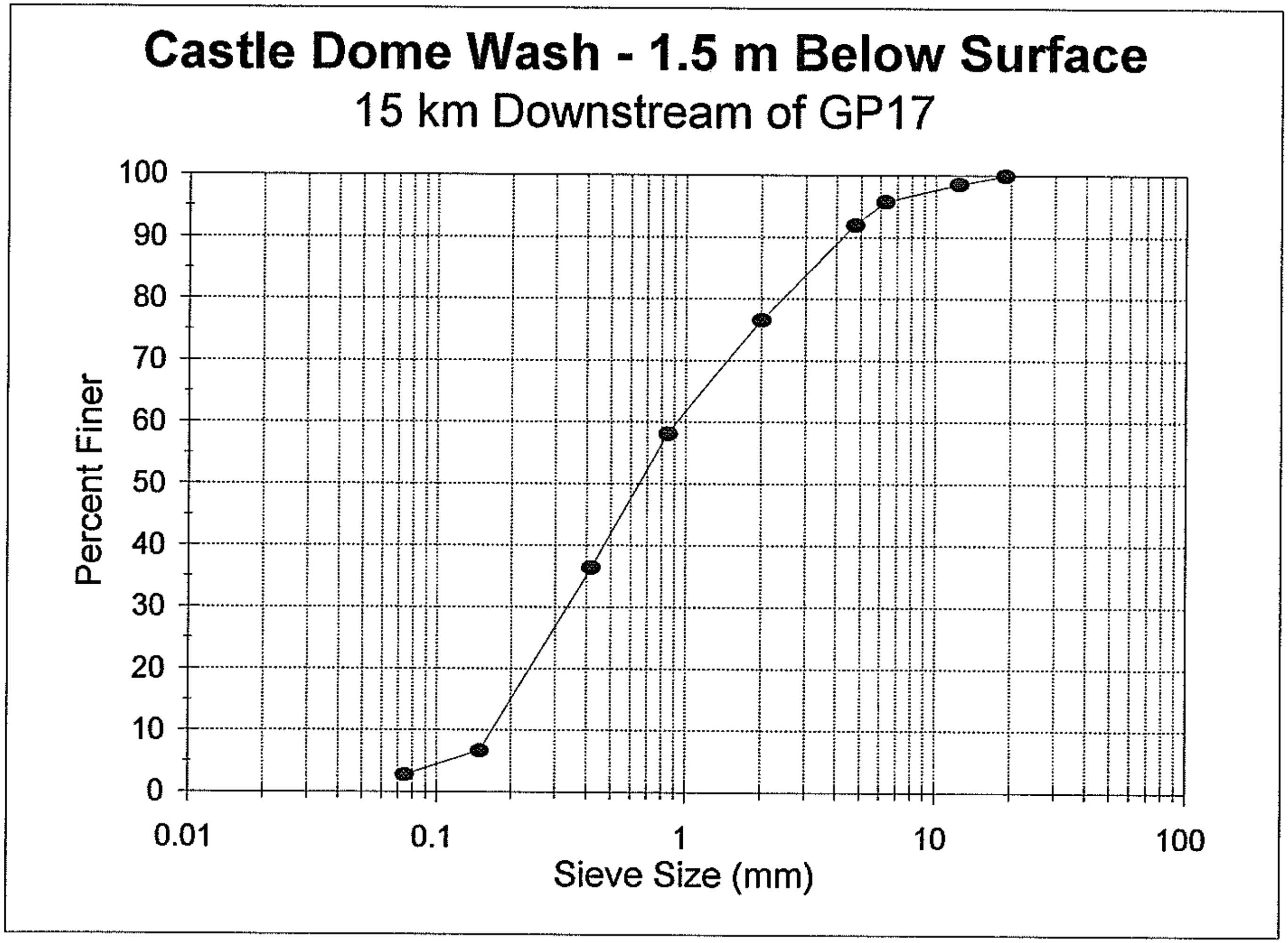
Sieve Size (mm)	Percent Finer (%)
19.000	100.0
12.500	99.6
6.300	96.2
4.750	93.3
2.000	77.3
0.850	53.9
0.420	27.9
0.150	1.0
0.075	0.3



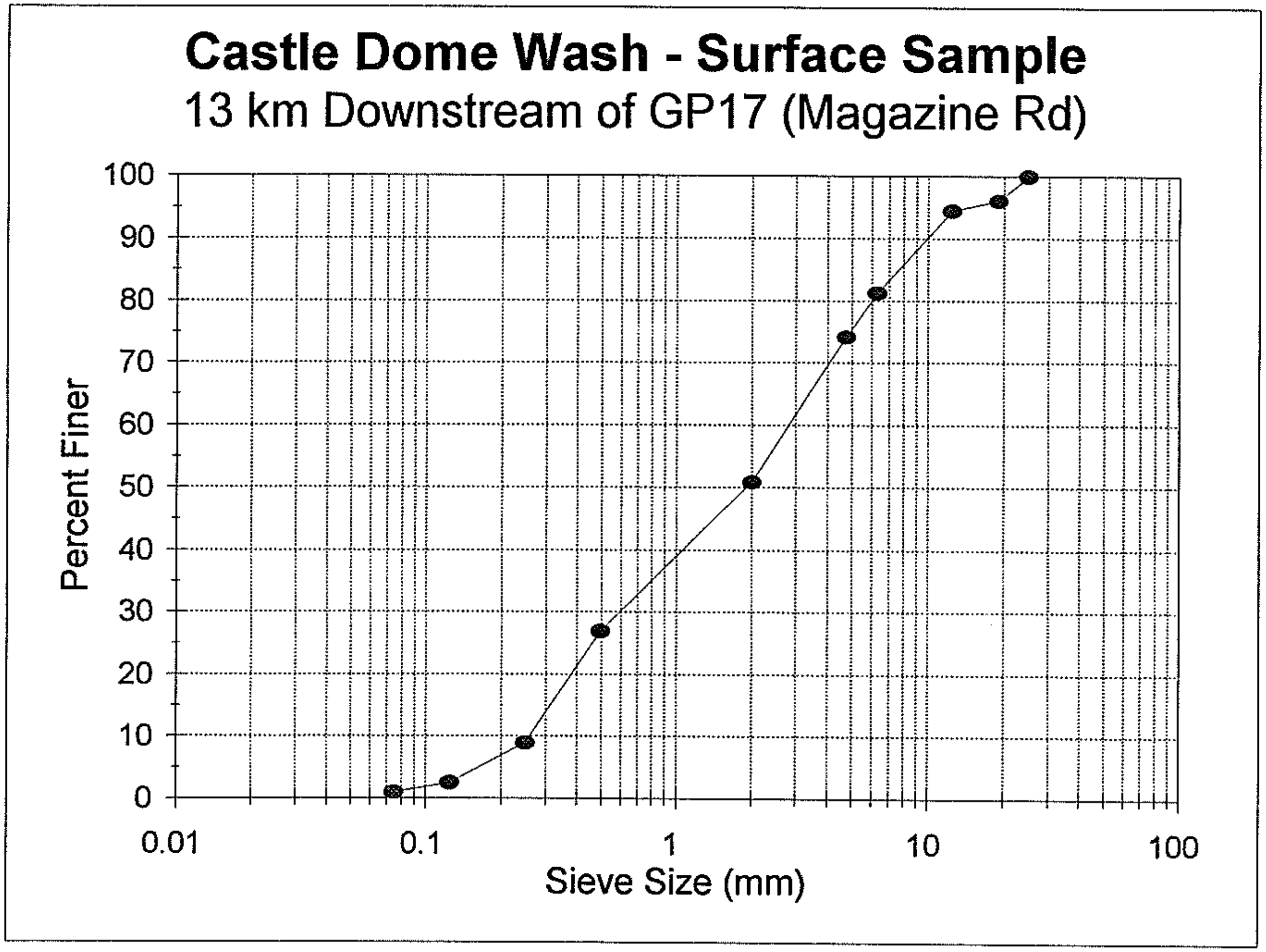
Sieve Size (mm)	Percent Finer (%)
19.000	100.0
12.500	98.3
6.300	85.2
4.750	77.1
2.000	45.4
0.500	7.2
0.250	2.3
0.125	1.0
0.075	0.5



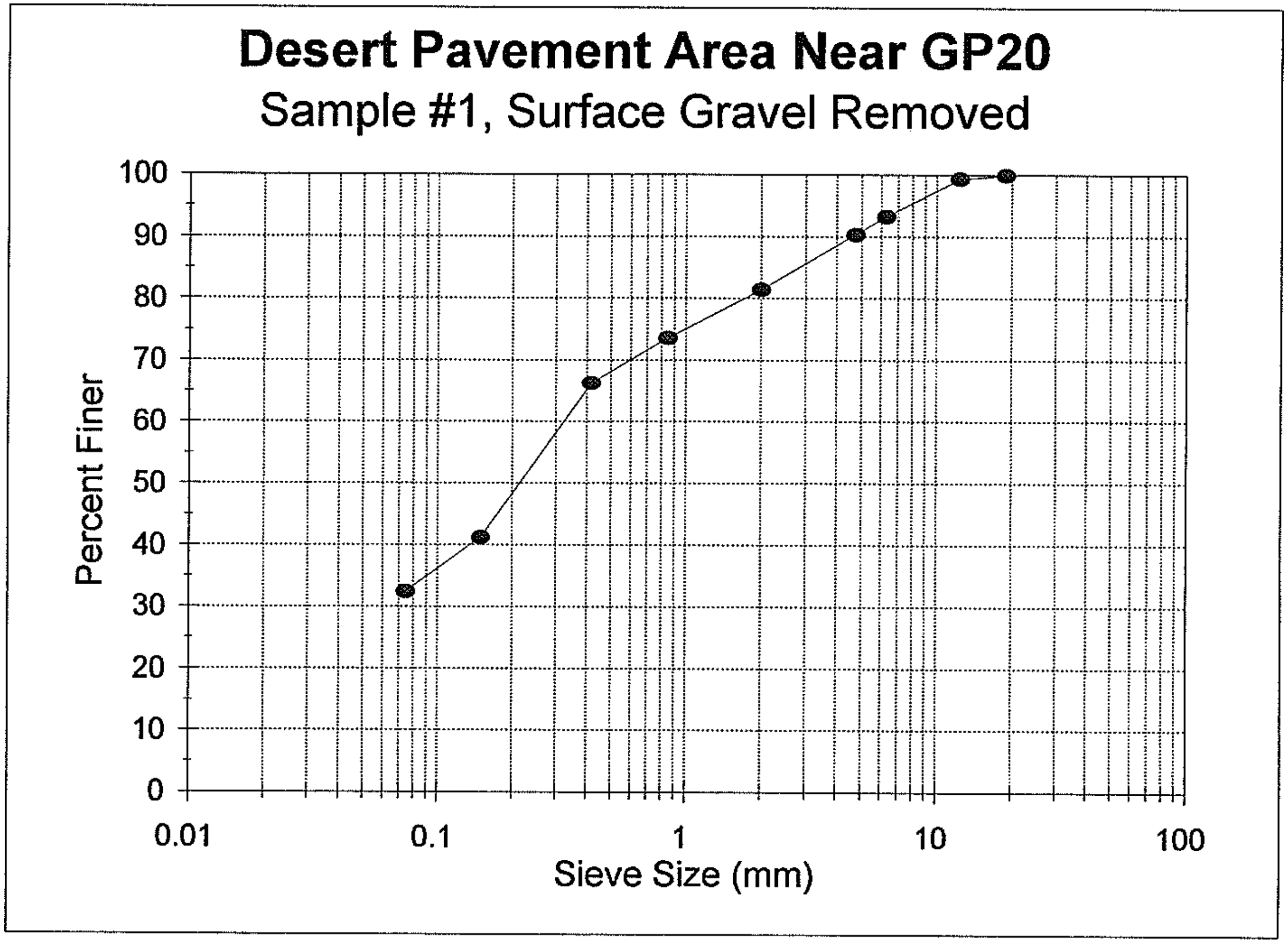
Sieve Size (mm)	Percent Finer (%)
19.000	100.0
12.500	98.6
6.300	95.8
4.750	92.0
2.000	76.6
0.850	58.2
0.420	36.5
0.150	6.8
0.075	2.8



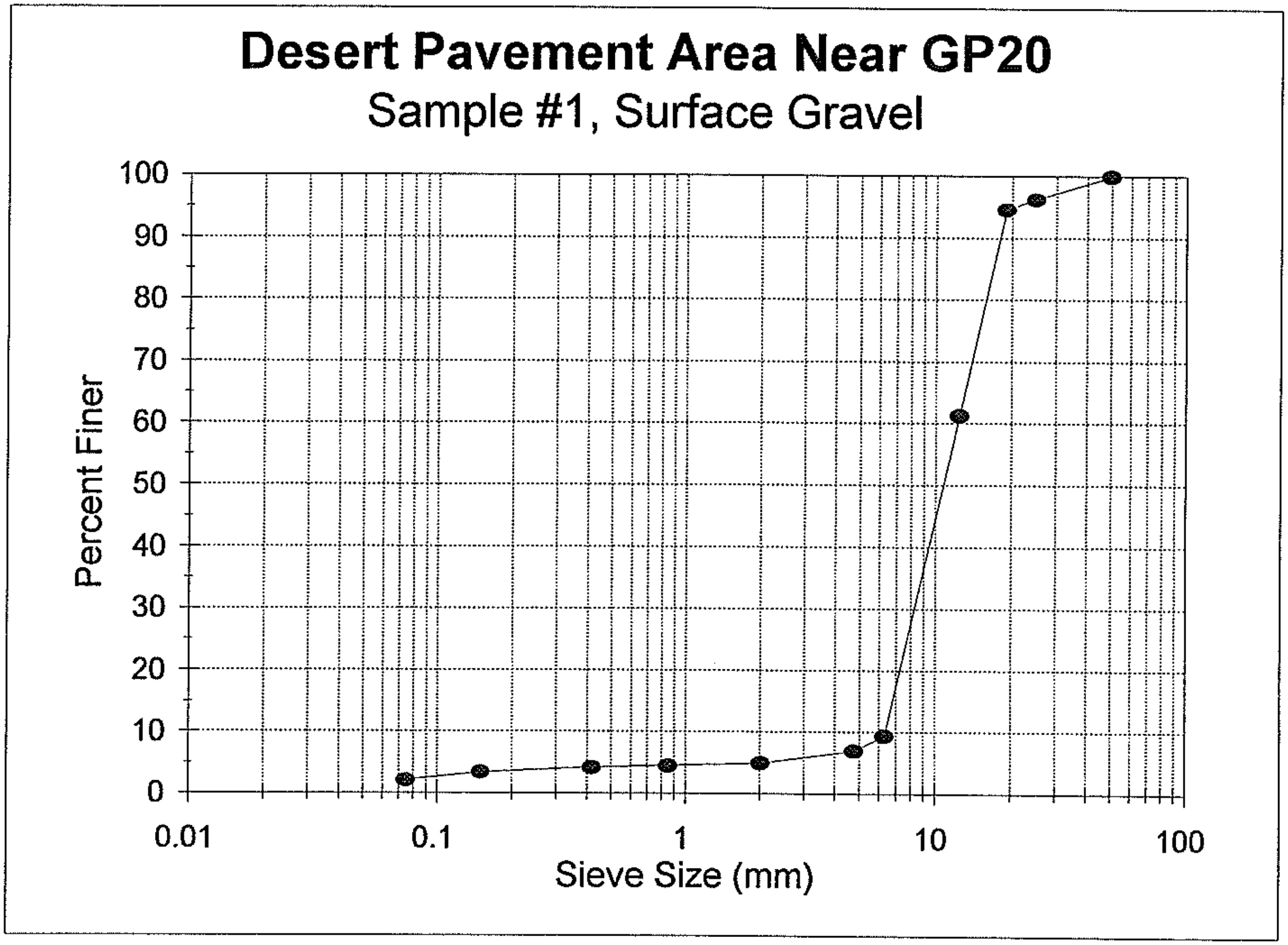
Sieve Size (mm)	Percent Finer (%)
25.000	100.0
19.000	96.1
12.500	94.5
6.300	81.3
4.750	74.2
2.000	50.9
0.500	27.0
0.250	9.0
0.125	2.5
0.075	1.0



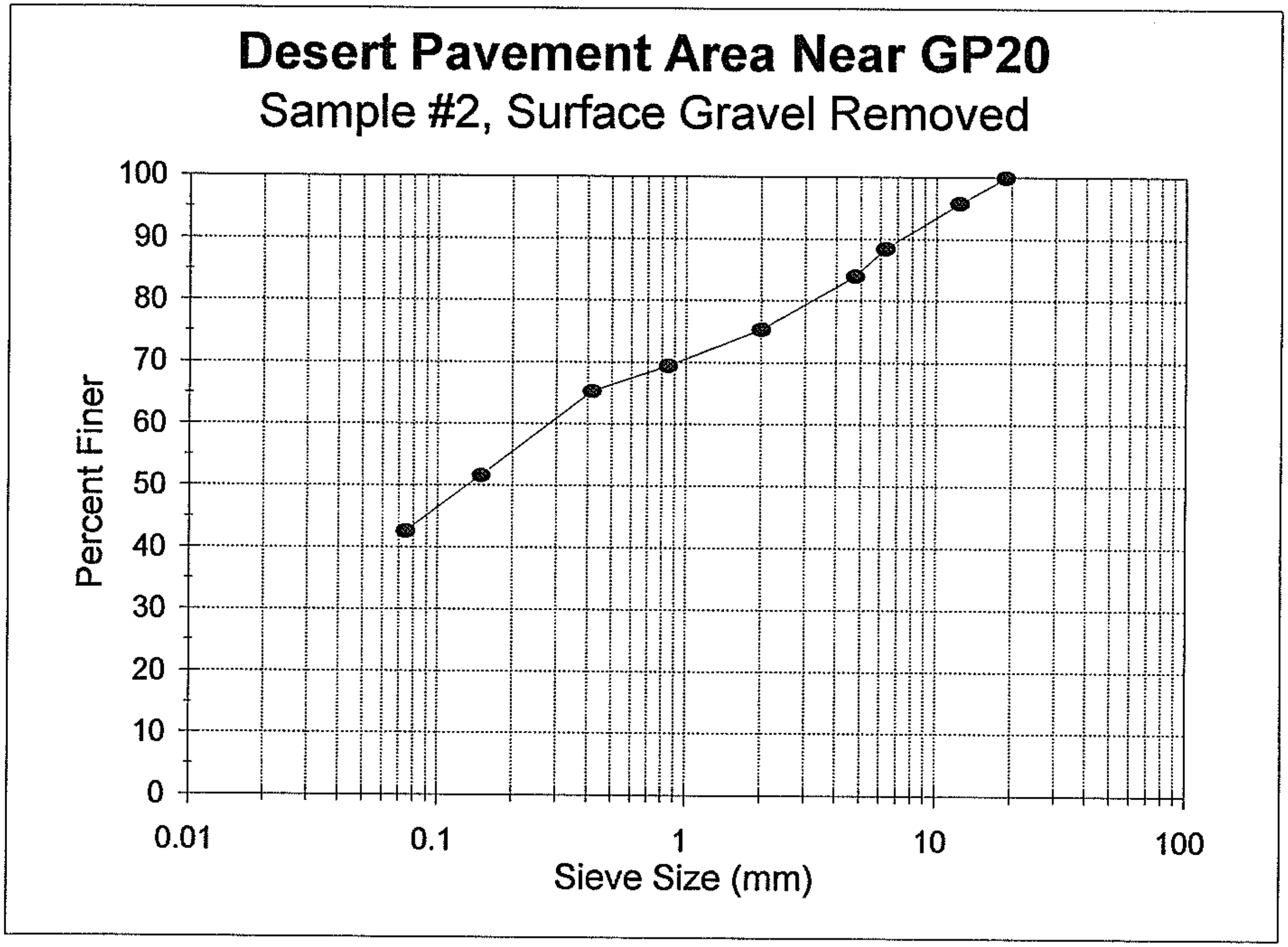
Sieve Size (mm)	Percent Finer (%)
19.000	100.0
12.500	99.4
6.300	93.3
4.750	90.4
2.000	81.5
0.850	73.6
0.420	66.3
0.150	41.3
0.075	32.5



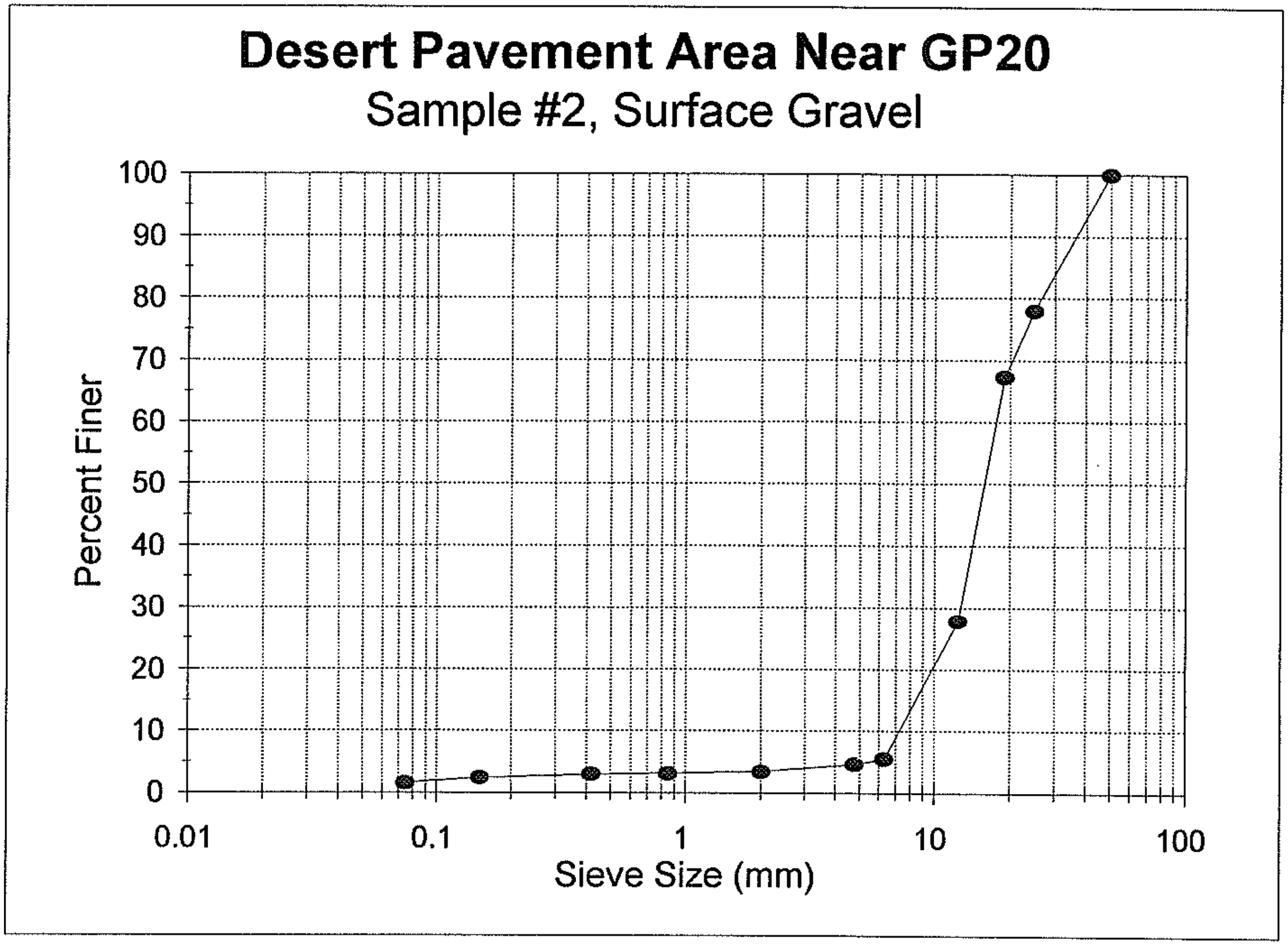
Sieve Size (mm)	Percent Finer (%)
50.000	100.0
25.000	96.2
19.000	94.6
12.500	61.3
6.300	9.5
4.750	7.0
2.000	5.0
0.850	4.5
0.420	4.2
0.150	3.4
0.075	2.1



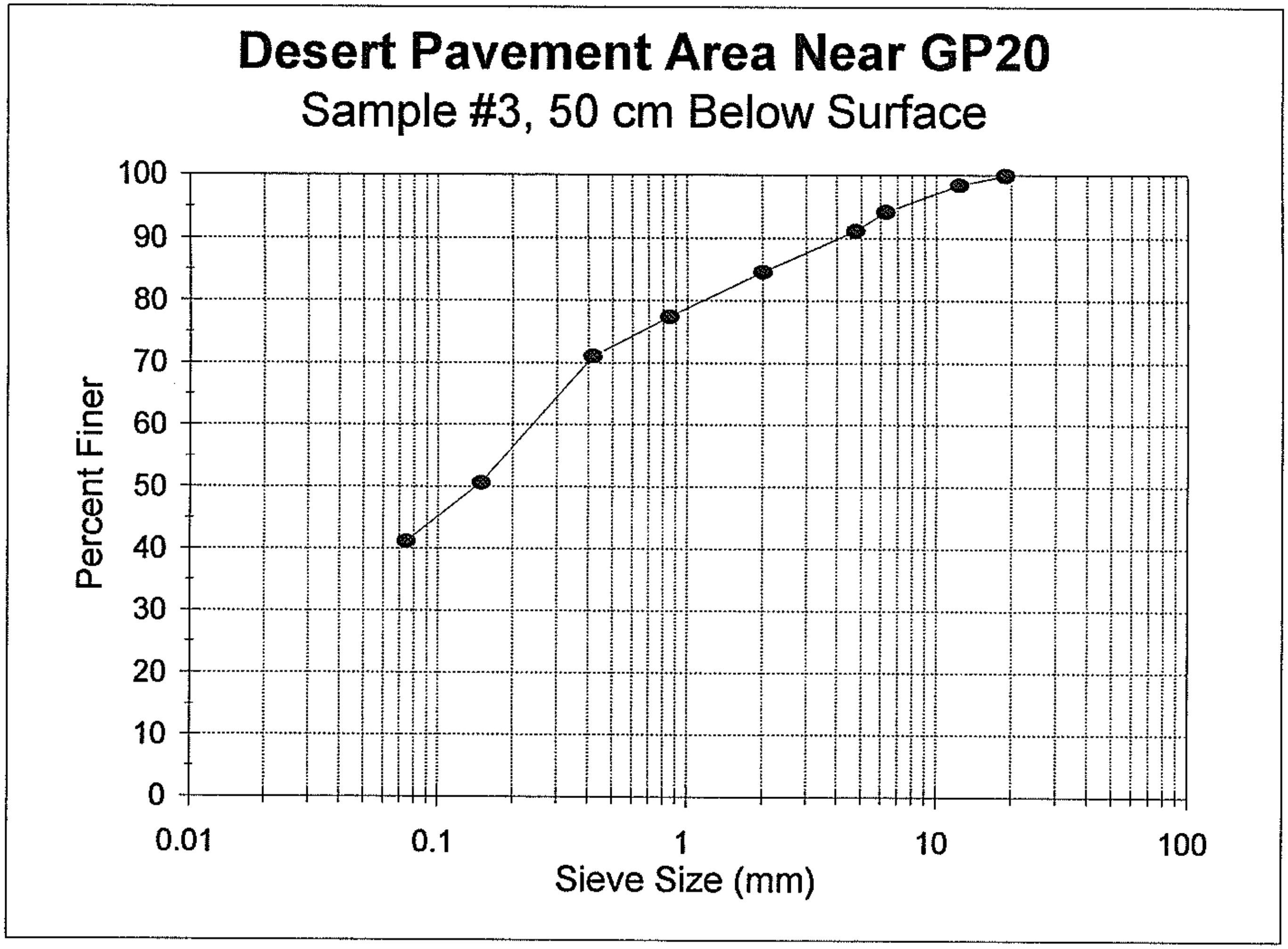
Sieve Size (mm)	Percent Finer (%)
19.000	100.0
12.500	95.8
6.300	88.5
4.750	84.0
2.000	75.3
0.850	69.4
0.420	65.3
0.150	51.7
0.075	42.6



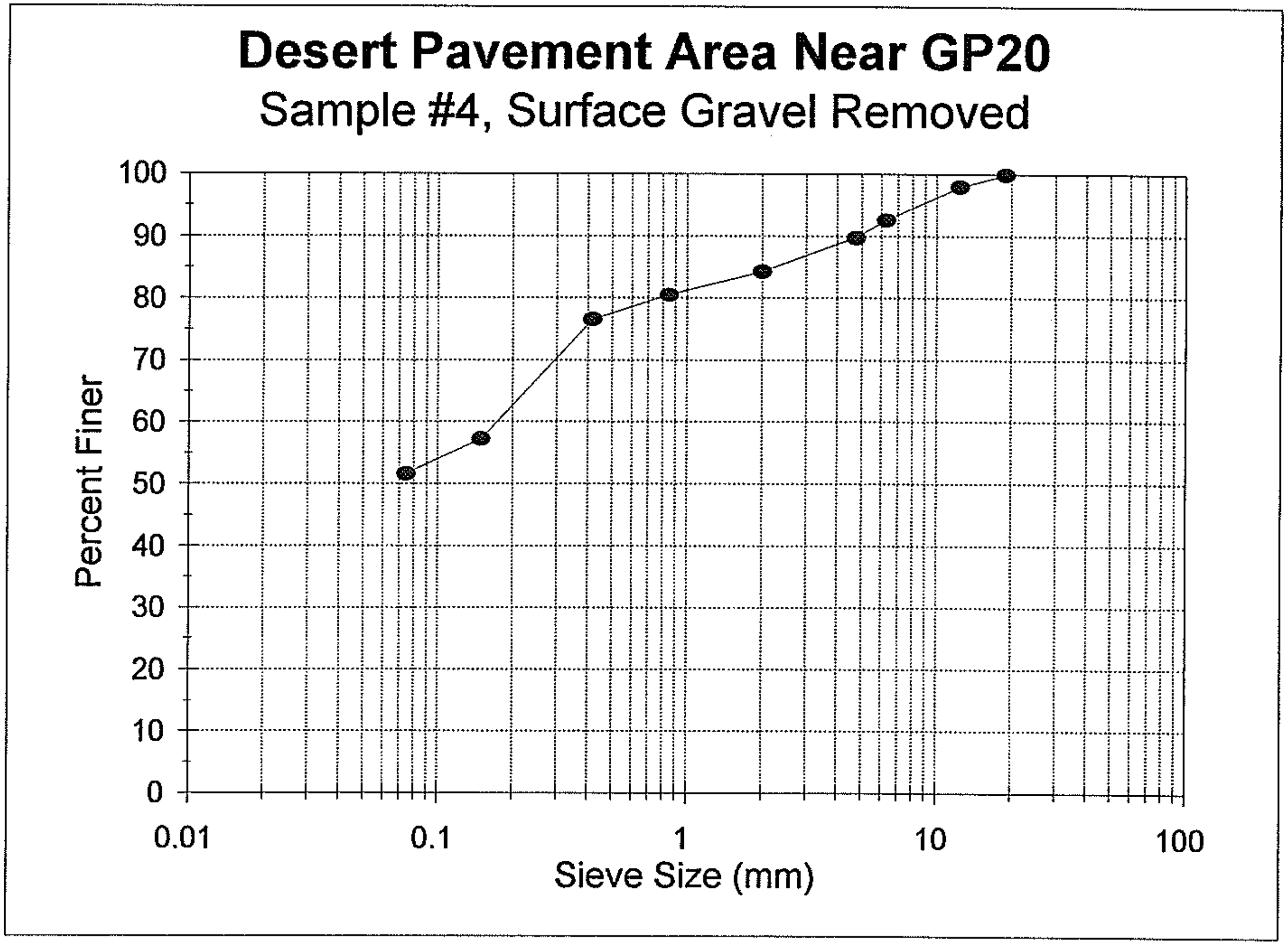
Sieve Size (mm)	Percent Finer (%)
50.000	100.0
25.000	78.0
19.000	67.3
12.500	27.9
6.300	5.6
4.750	4.7
2.000	3.5
0.850	3.2
0.420	3.0
0.150	2.4
0.075	1.6



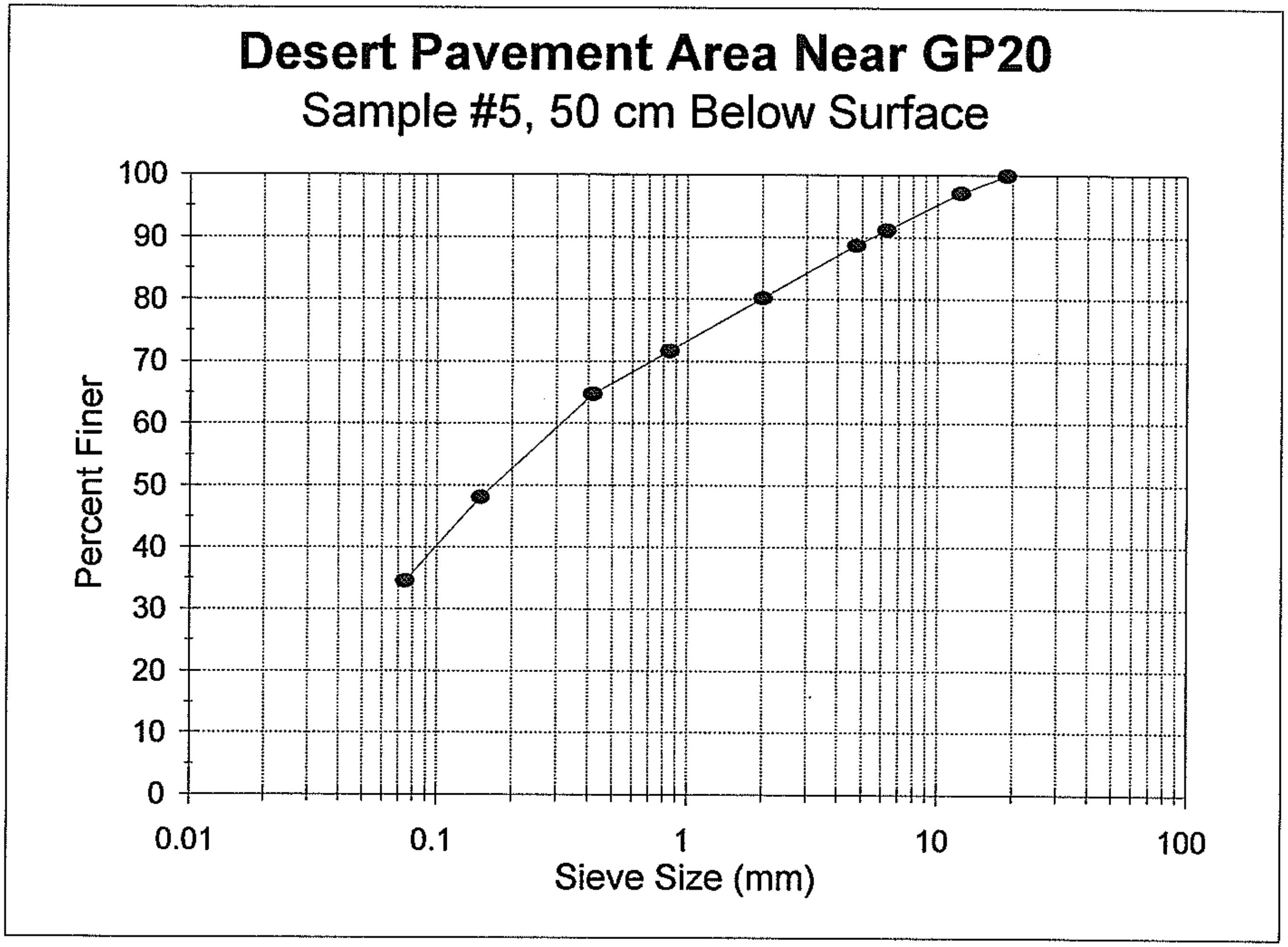
Sieve Size (mm)	Percent Finer (%)
19.000	100.0
12.500	98.5
6.300	94.2
4.750	91.2
2.000	84.7
0.850	77.5
0.420	71.1
0.150	50.7
0.075	41.2



Sieve Size (mm)	Percent Finer (%)
19.000	100.0
12.500	98.0
6.300	92.6
4.750	89.8
2.000	84.3
0.850	80.6
0.420	76.6
0.150	57.3
0.075	51.7



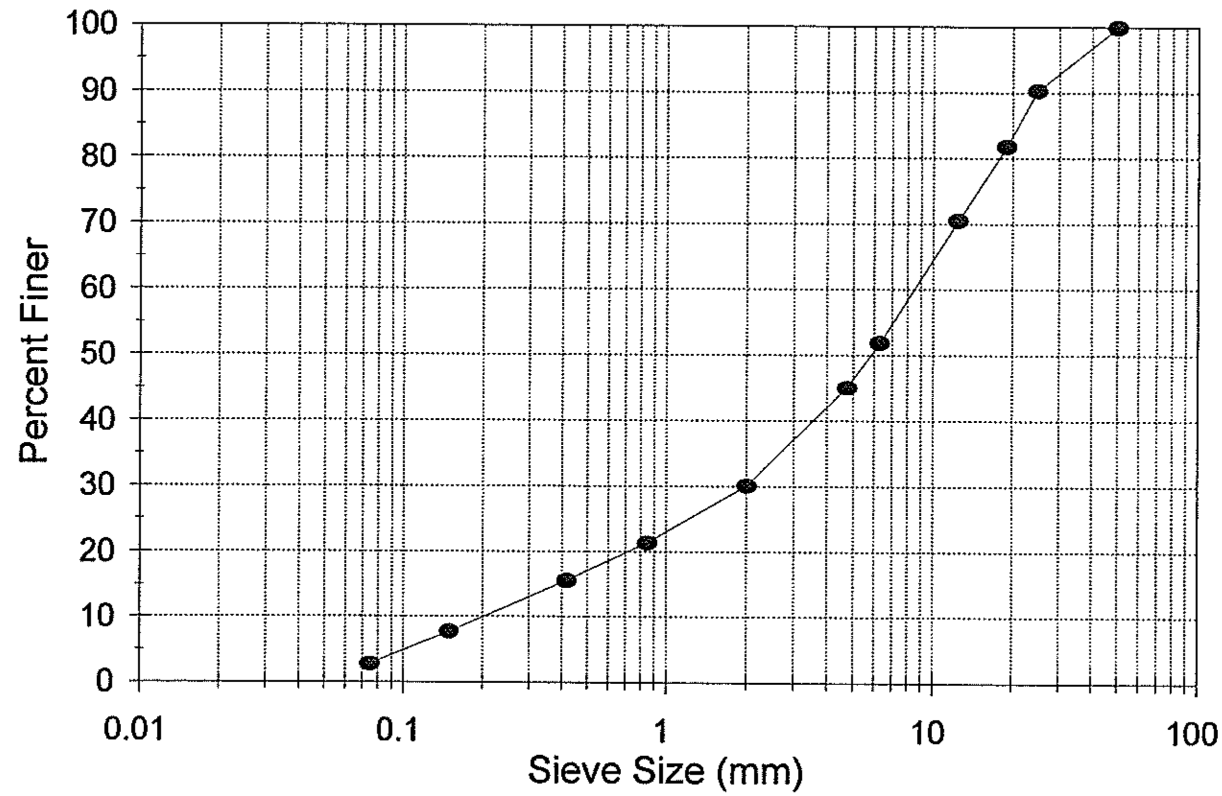
Sieve Size (mm)	Percent Finer (%)
19.000	100.0
12.500	97.1
6.300	91.2
4.750	88.7
2.000	80.3
0.850	71.7
0.420	64.8
0.150	48.2
0.075	34.6



Sieve Size (mm)	Percent Finer (%)
50.000	100.0
25.000	90.3
19.000	81.9
12.500	70.5
6.300	51.9
4.750	45.1
2.000	30.1
0.850	21.4
0.420	15.6
0.150	7.8
0.075	2.8

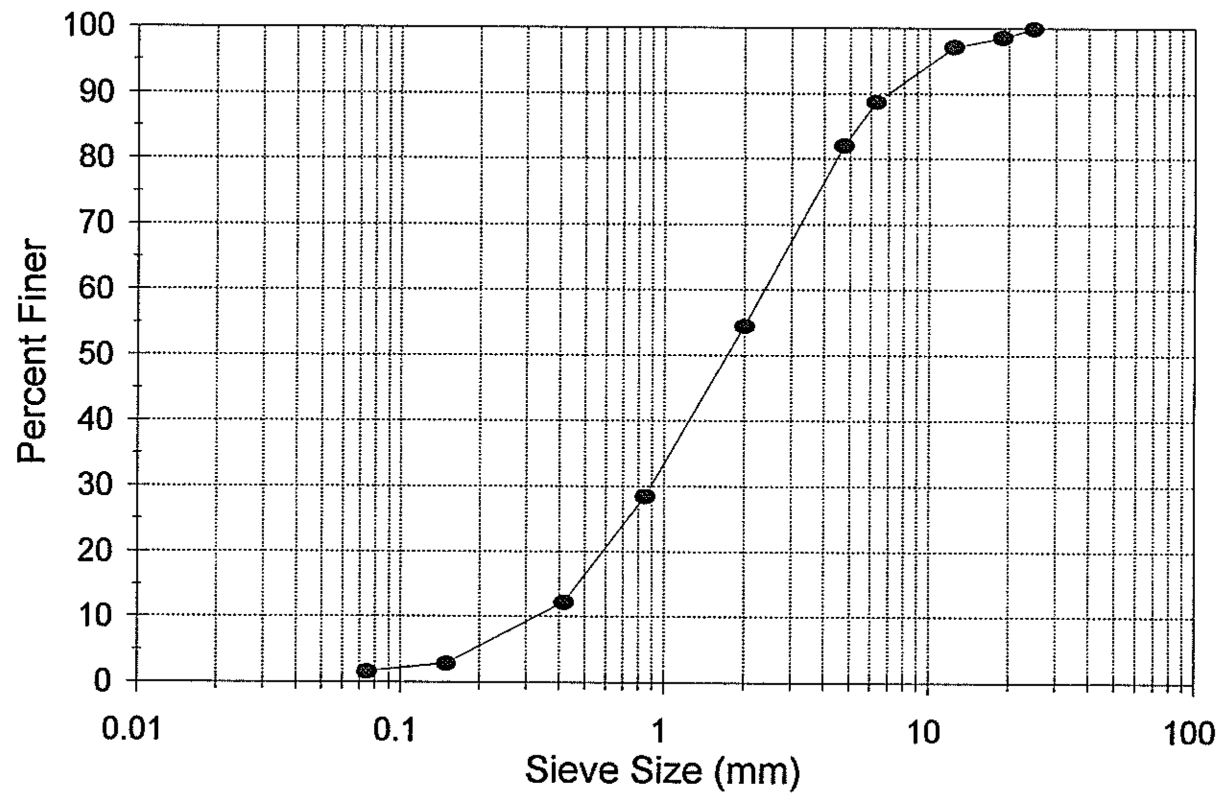
Desert Pavement Area Near GP20

Sample #6, Surface Sample With Gravel

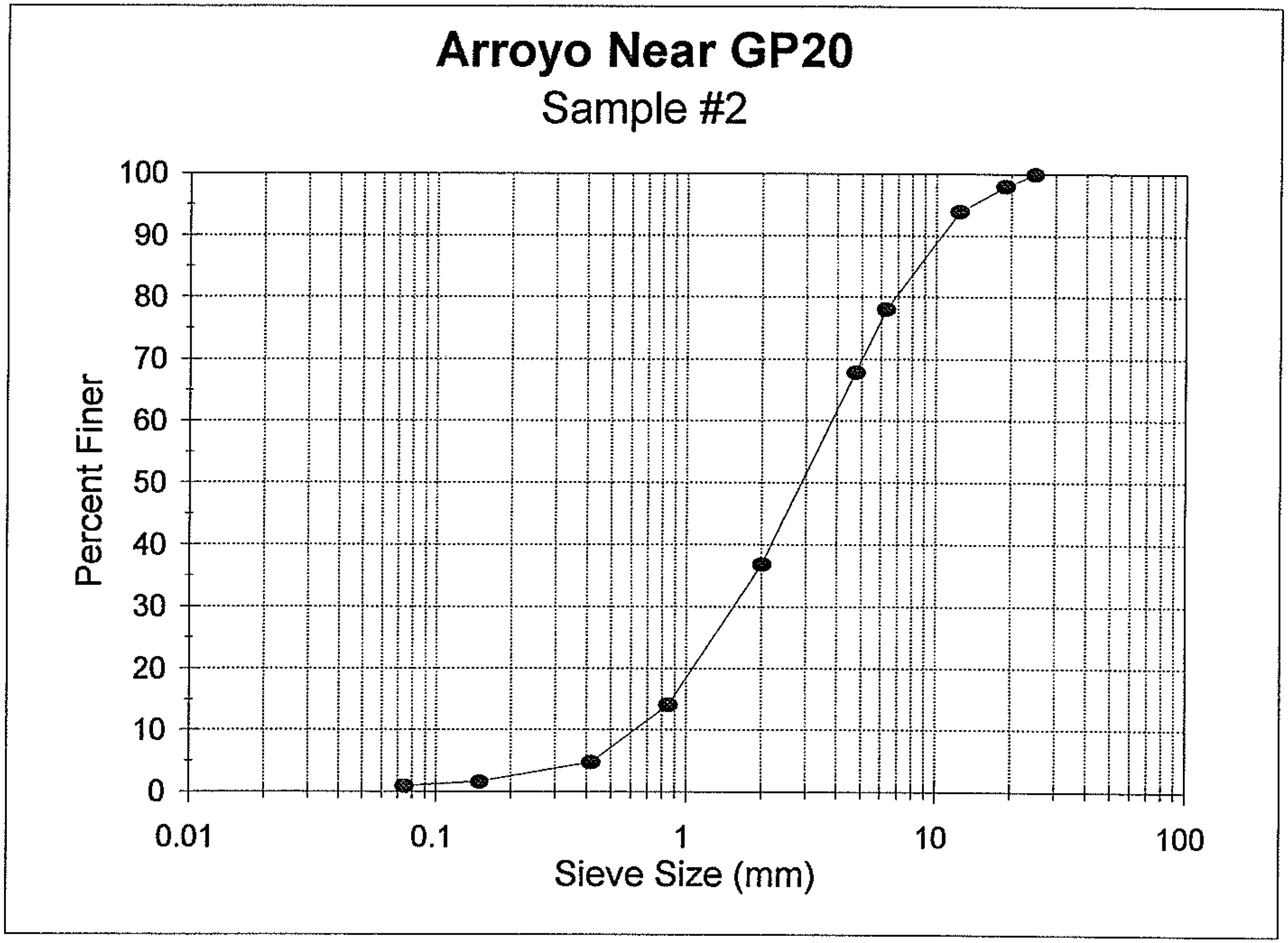


Sieve Size (mm)	Percent Finer (%)
25.000	100.0
19.000	98.6
12.500	97.1
6.300	88.7
4.750	82.1
2.000	54.5
0.850	28.5
0.420	12.3
0.150	2.9
0.075	1.6

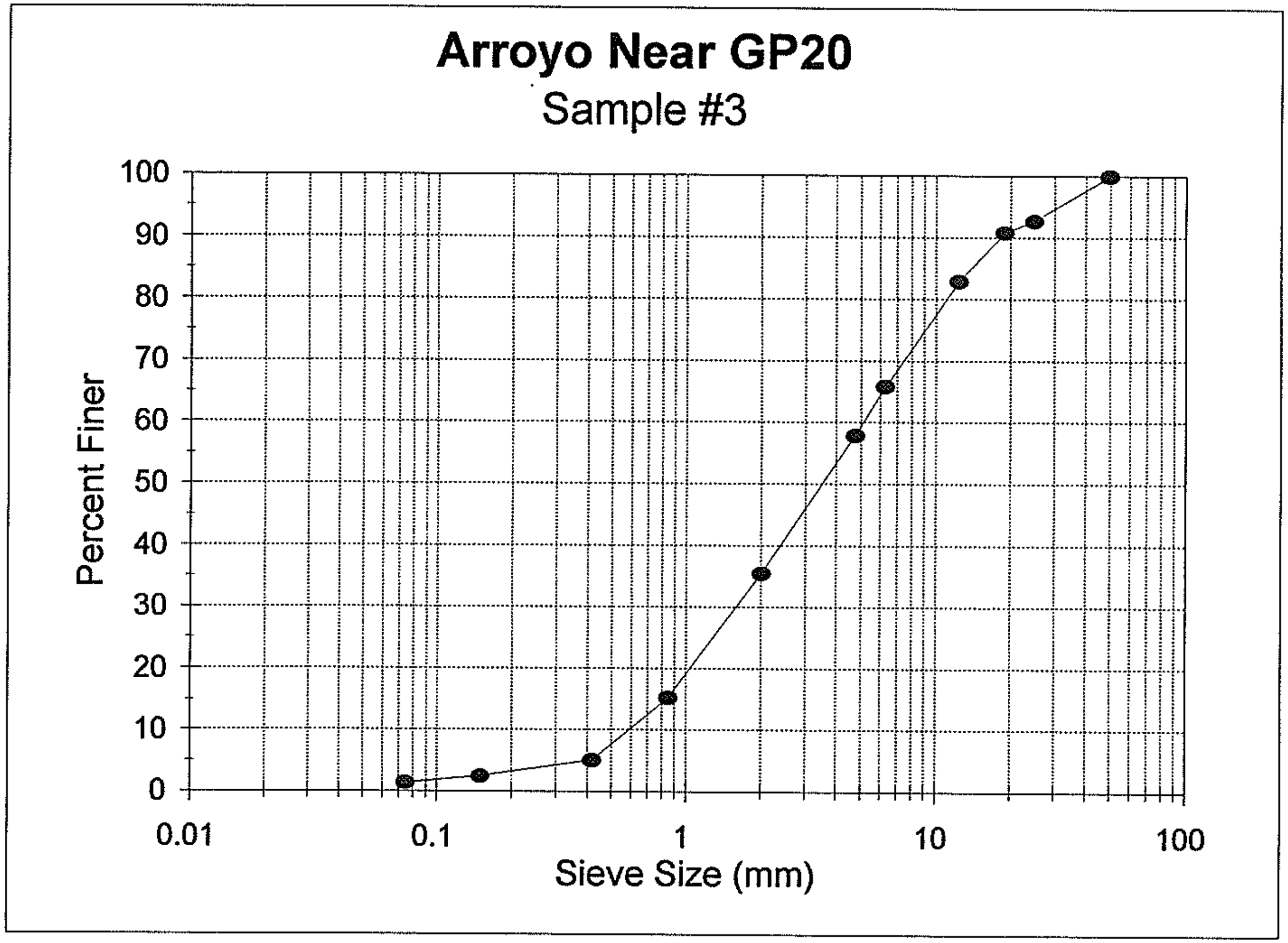
Arroyo Near GP20
Sample #1



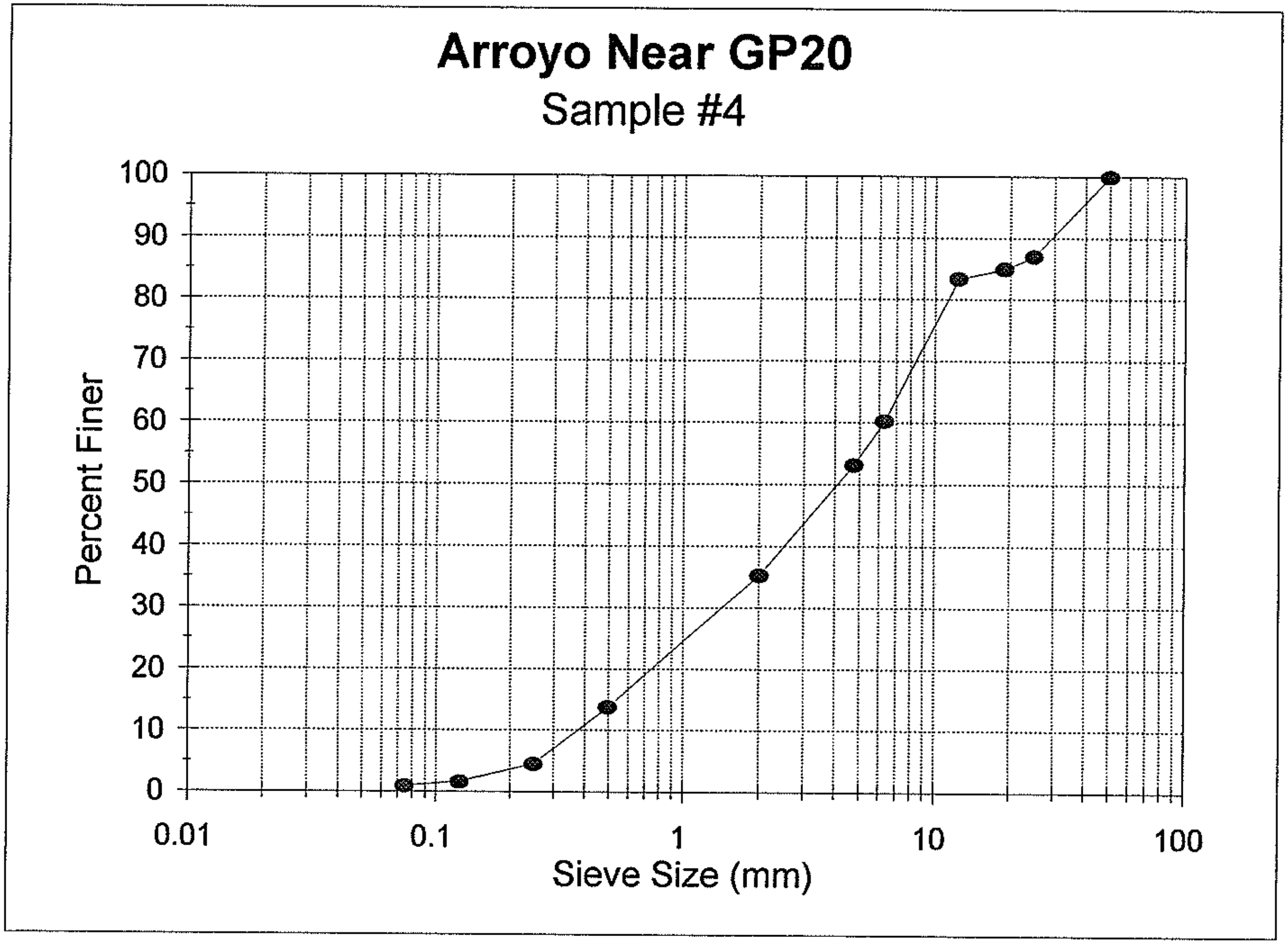
Sieve Size (mm)	Percent Finer (%)
25.000	100.0
19.000	98.0
12.500	93.9
6.300	78.1
4.750	67.9
2.000	36.9
0.850	14.1
0.420	4.8
0.150	1.6
0.075	0.9



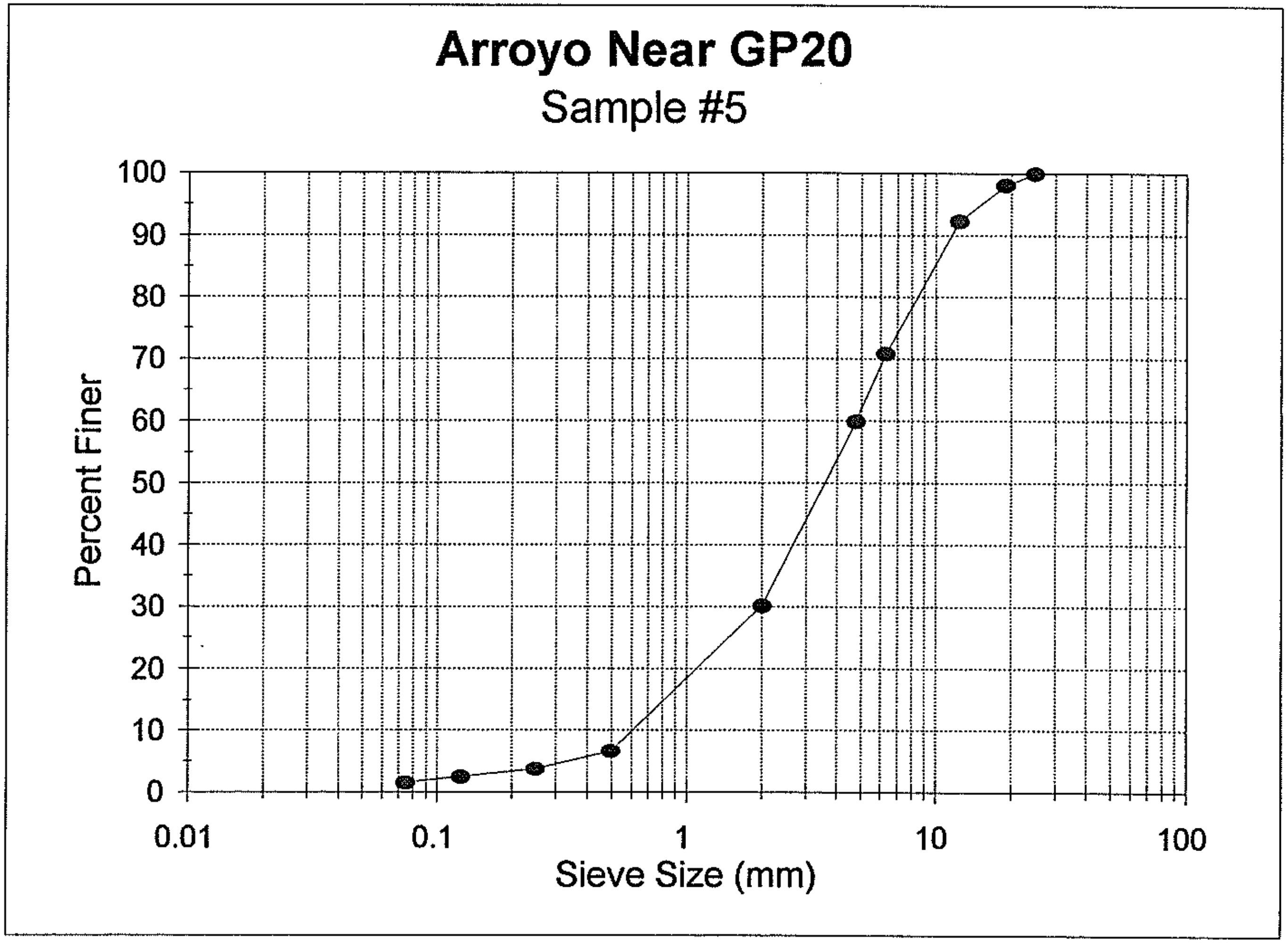
Sieve Size (mm)	Percent Finer (%)
50.000	100.0
25.000	92.7
19.000	90.8
12.500	83.0
6.300	65.8
4.750	57.9
2.000	35.5
0.850	15.3
0.420	5.1
0.150	2.5
0.075	1.4



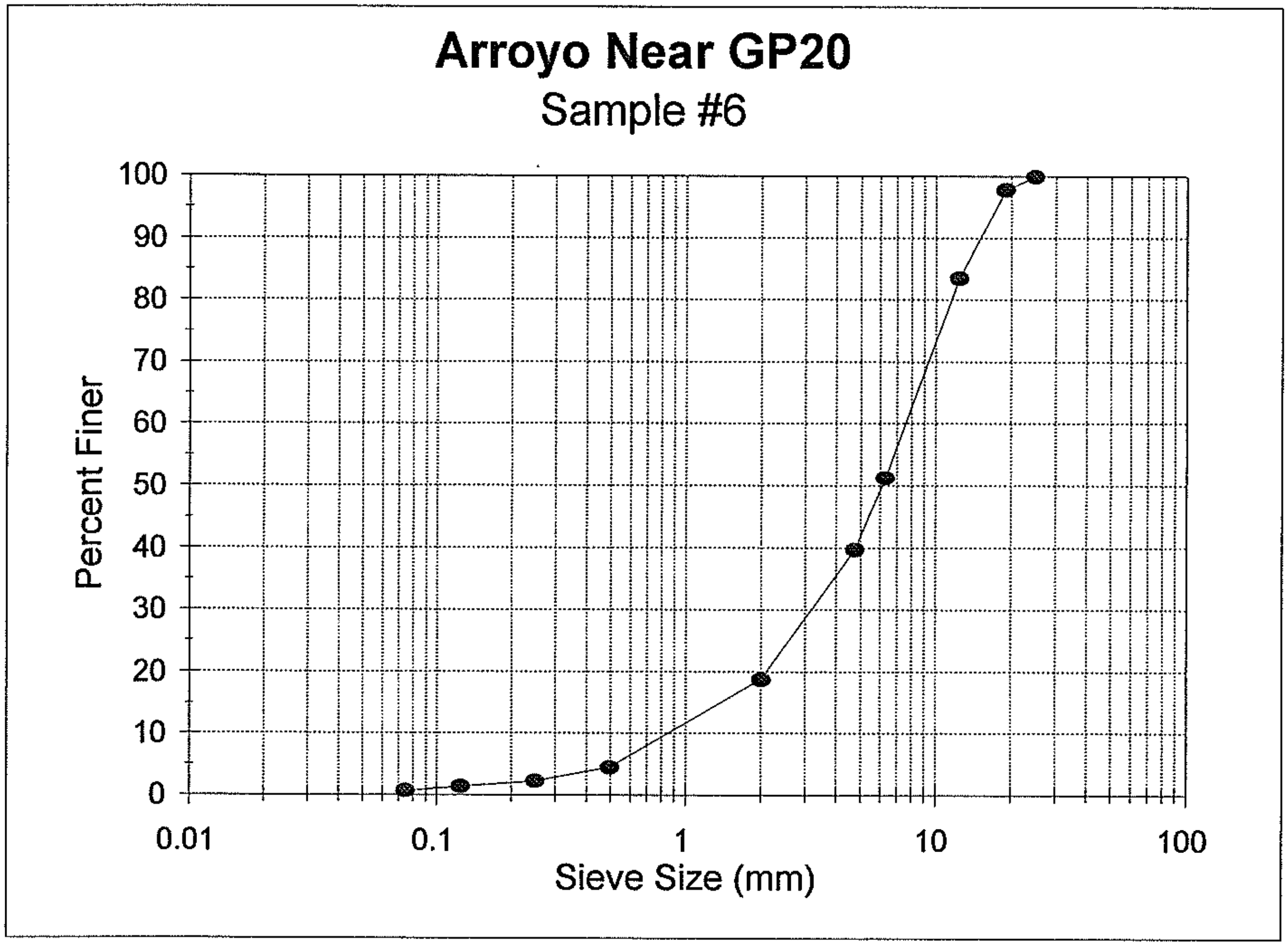
Sieve Size (mm)	Percent Finer (%)
50.000	100.0
25.000	87.0
19.000	85.0
12.500	83.4
6.300	60.3
4.750	53.2
2.000	35.3
0.500	13.8
0.250	4.5
0.125	1.6
0.075	0.9



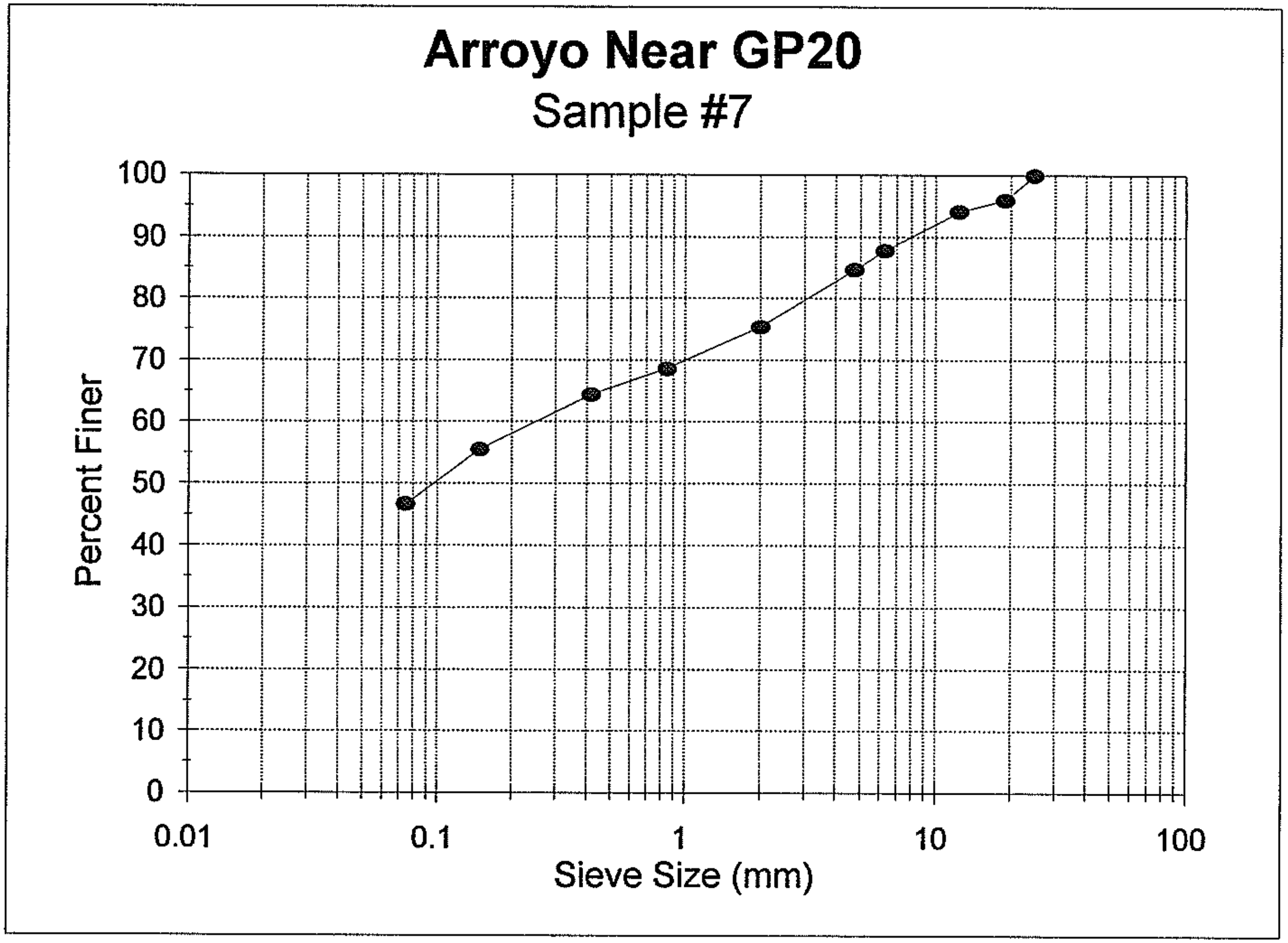
Sieve Size (mm)	Percent Finer (%)
25.000	100.0
19.000	98.1
12.500	92.3
6.300	70.8
4.750	59.9
2.000	30.2
0.500	6.7
0.250	3.8
0.125	2.5
0.075	1.5



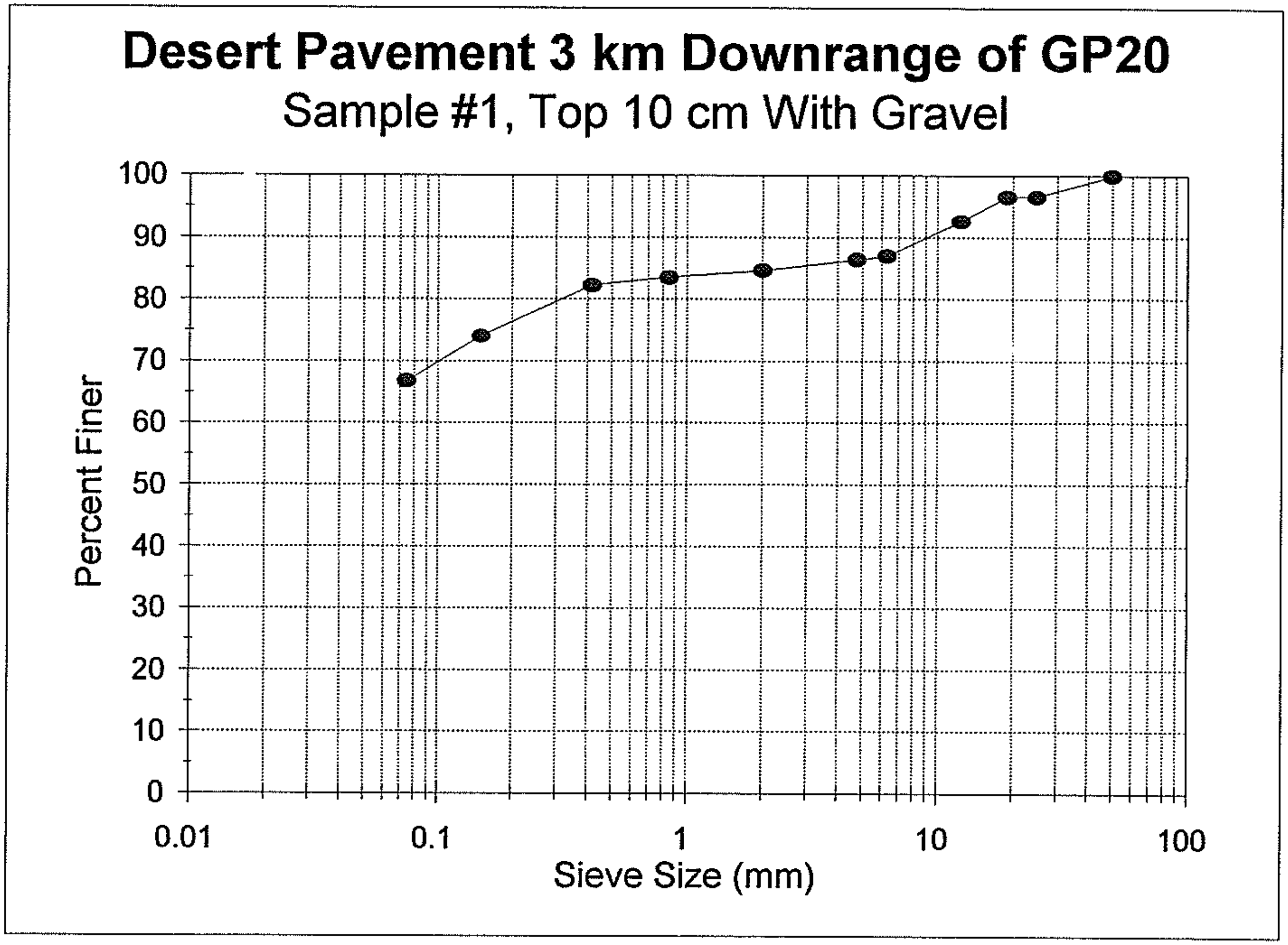
Sieve Size (mm)	Percent Finer (%)
25.000	100.0
19.000	97.8
12.500	83.6
6.300	51.3
4.750	39.8
2.000	18.8
0.500	4.5
0.250	2.3
0.125	1.4
0.075	0.7



Sieve Size (mm)	Percent Finer (%)
25.000	100.0
19.000	96.0
12.500	94.1
6.300	87.8
4.750	84.7
2.000	75.4
0.850	68.6
0.420	64.4
0.149	55.6
0.075	46.7



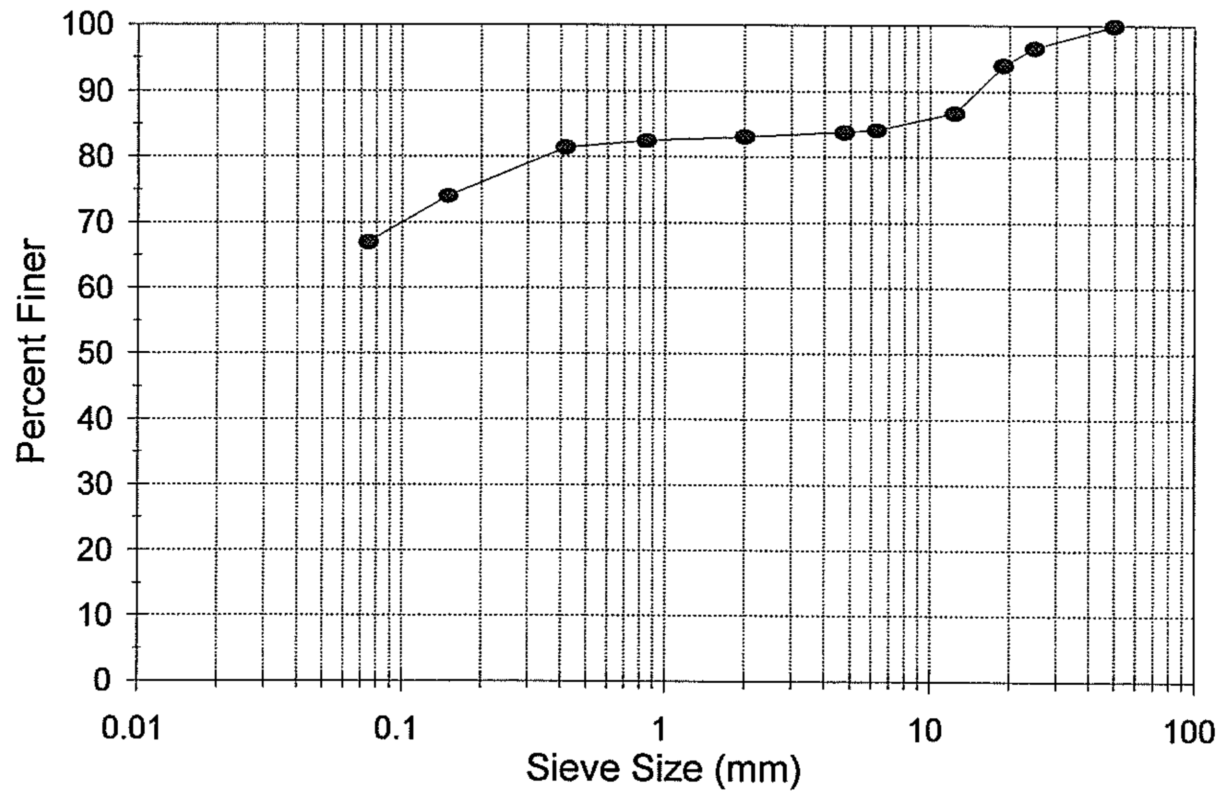
Sieve Size (mm)	Percent Finer (%)
50.000	100.0
25.000	96.6
19.000	96.6
12.500	92.6
6.300	87.0
4.750	86.4
2.000	84.7
0.850	83.6
0.420	82.3
0.150	74.1
0.075	66.8



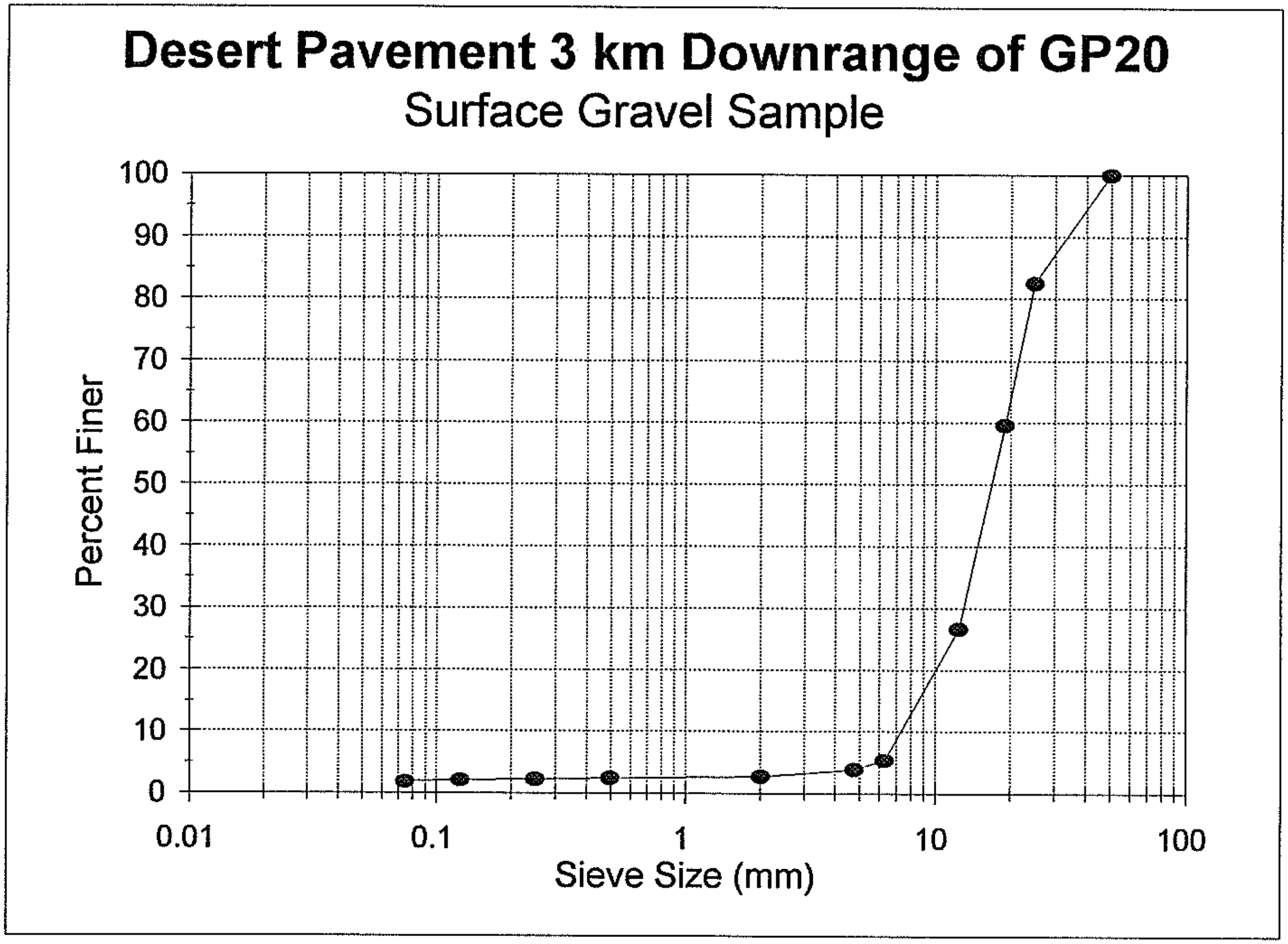
Sieve Size (mm)	Percent Finer (%)
50.000	100.0
25.000	96.6
19.000	93.9
12.500	86.8
6.300	84.2
4.750	83.9
2.000	83.1
0.850	82.5
0.420	81.5
0.150	74.1
0.075	67.0

Desert Pavement 3km Downrange of GP20

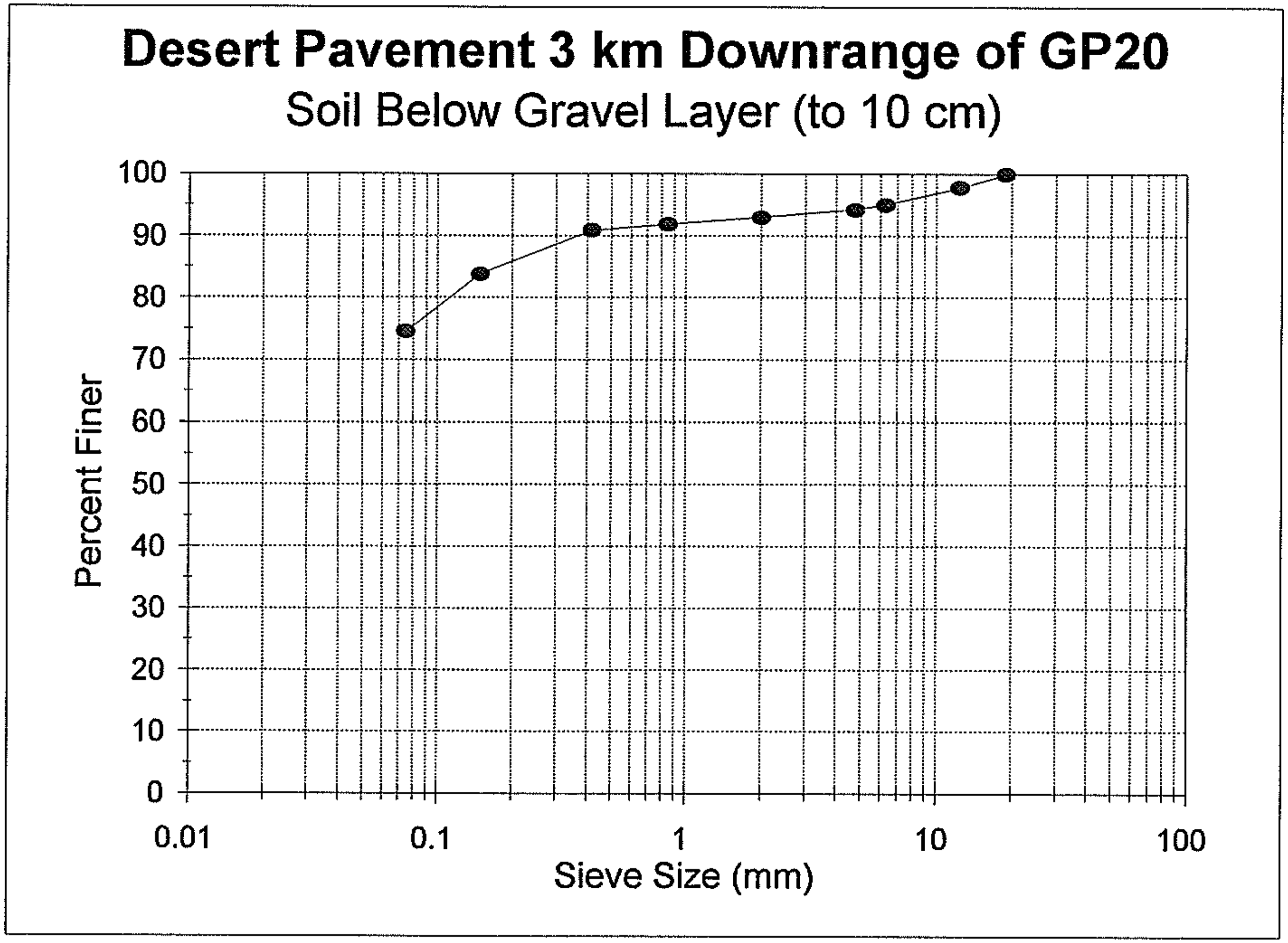
Sample #2, Top 10 cm With Gravel



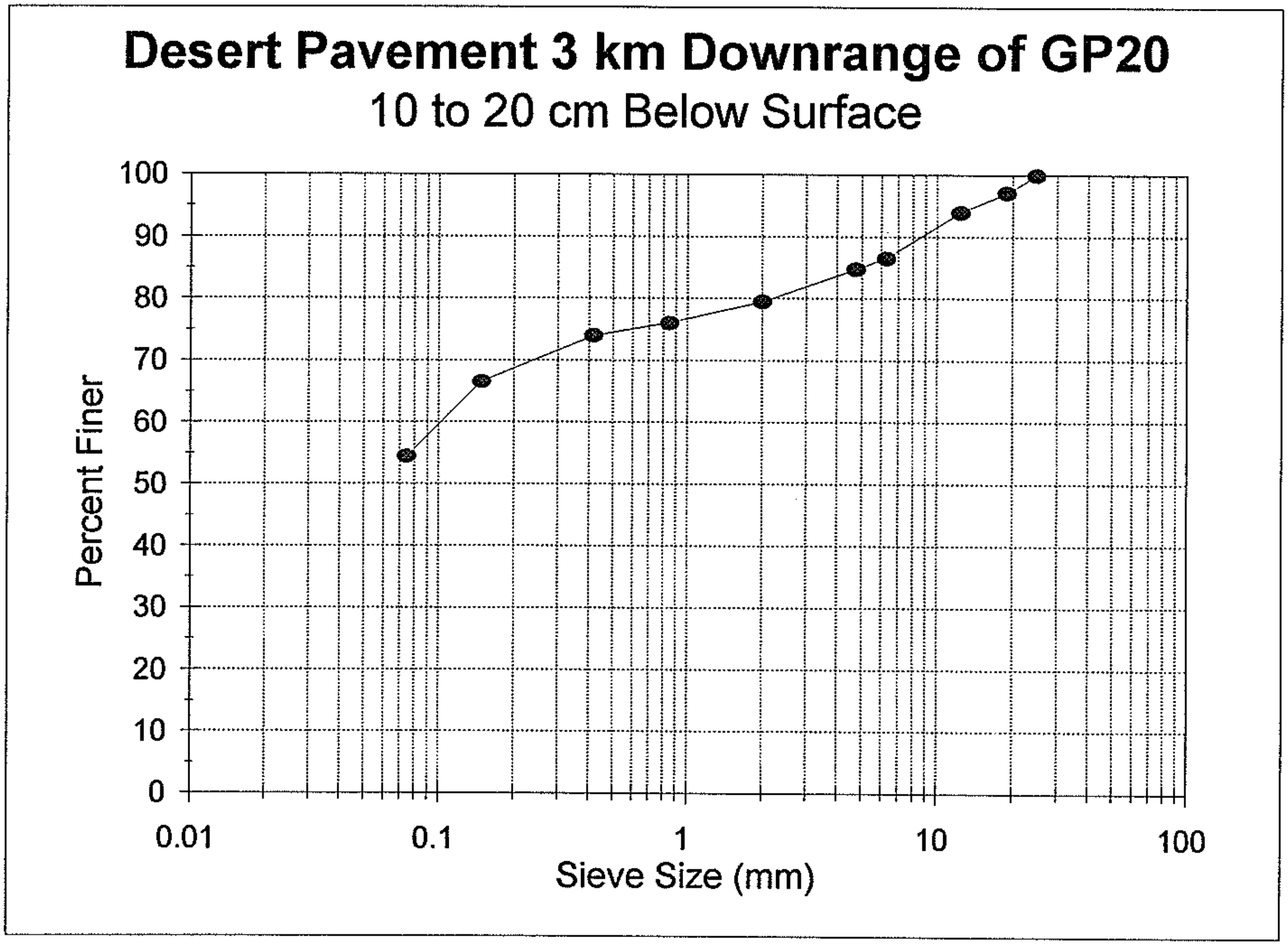
Sieve Size (mm)	Percent Finer (%)
50.000	100.0
25.000	82.6
19.000	59.6
12.500	26.7
6.300	5.4
4.750	3.9
2.000	2.7
0.500	2.4
0.250	2.3
0.125	2.1
0.075	1.8



Sieve Size (mm)	Percent Finer (%)
19.000	100.0
12.500	97.8
6.300	95.0
4.750	94.3
2.000	93.0
0.850	91.9
0.420	90.9
0.149	83.9
0.075	74.6



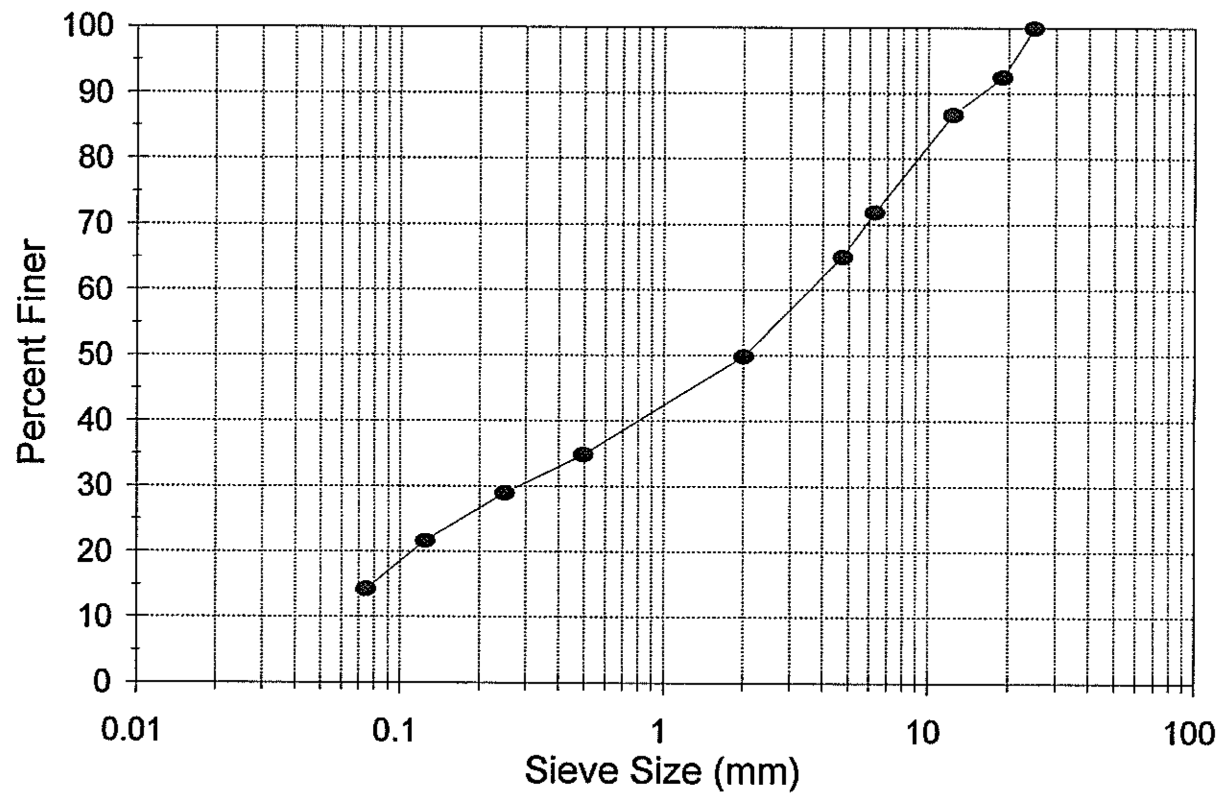
Sieve Size (mm)	Percent Finer (%)
25.000	100.0
19.000	97.1
12.500	94.0
6.300	86.6
4.750	84.8
2.000	79.5
0.850	76.1
0.420	74.0
0.149	66.6
0.075	54.5



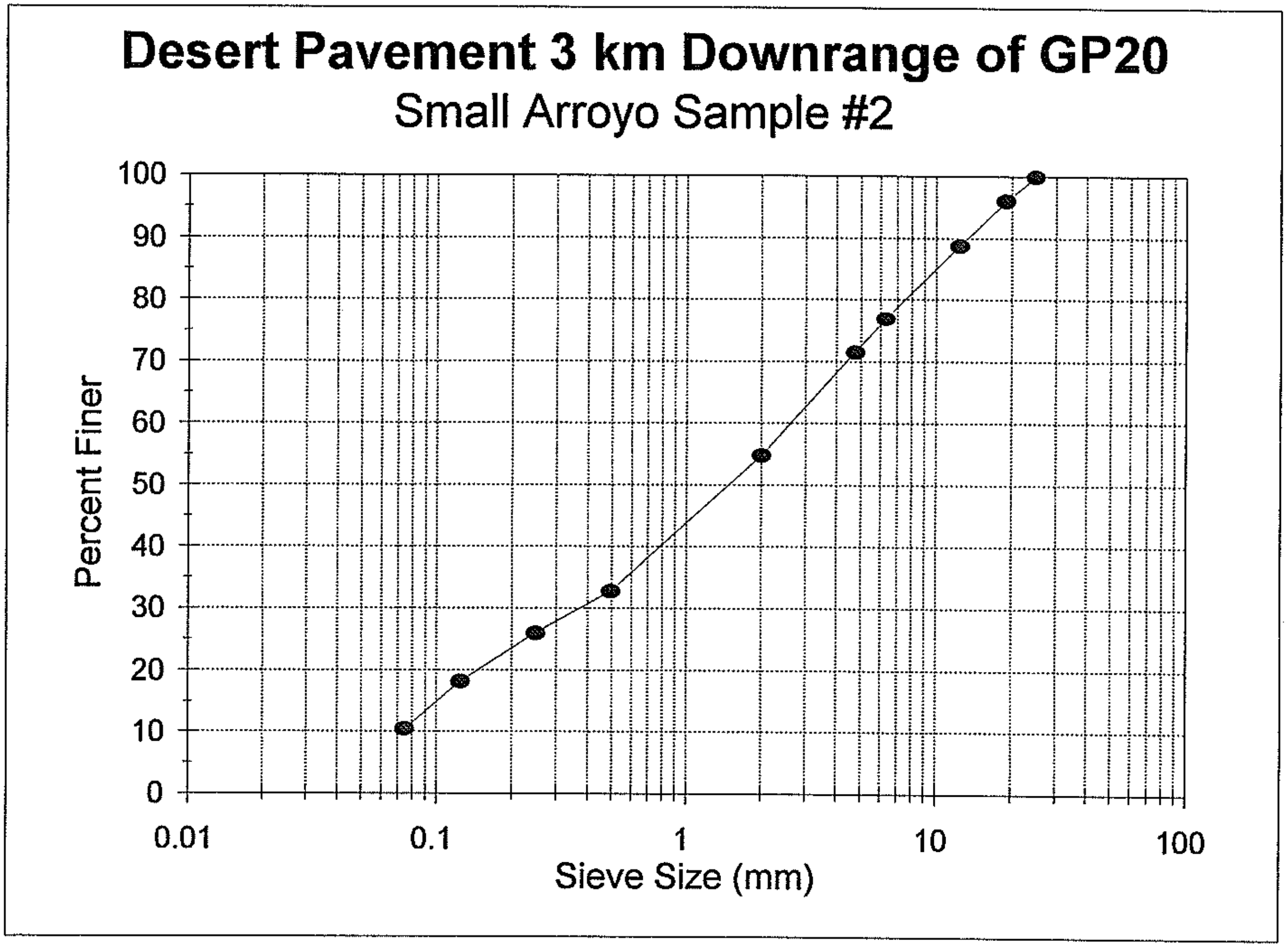
Sieve Size (mm)	Percent Finer (%)
25.000	100.0
19.000	92.5
12.500	86.8
6.300	71.9
4.750	65.1
2.000	49.9
0.500	34.9
0.250	29.0
0.125	21.7
0.075	14.3

Desert Pavement 3 km Downrange of GP20

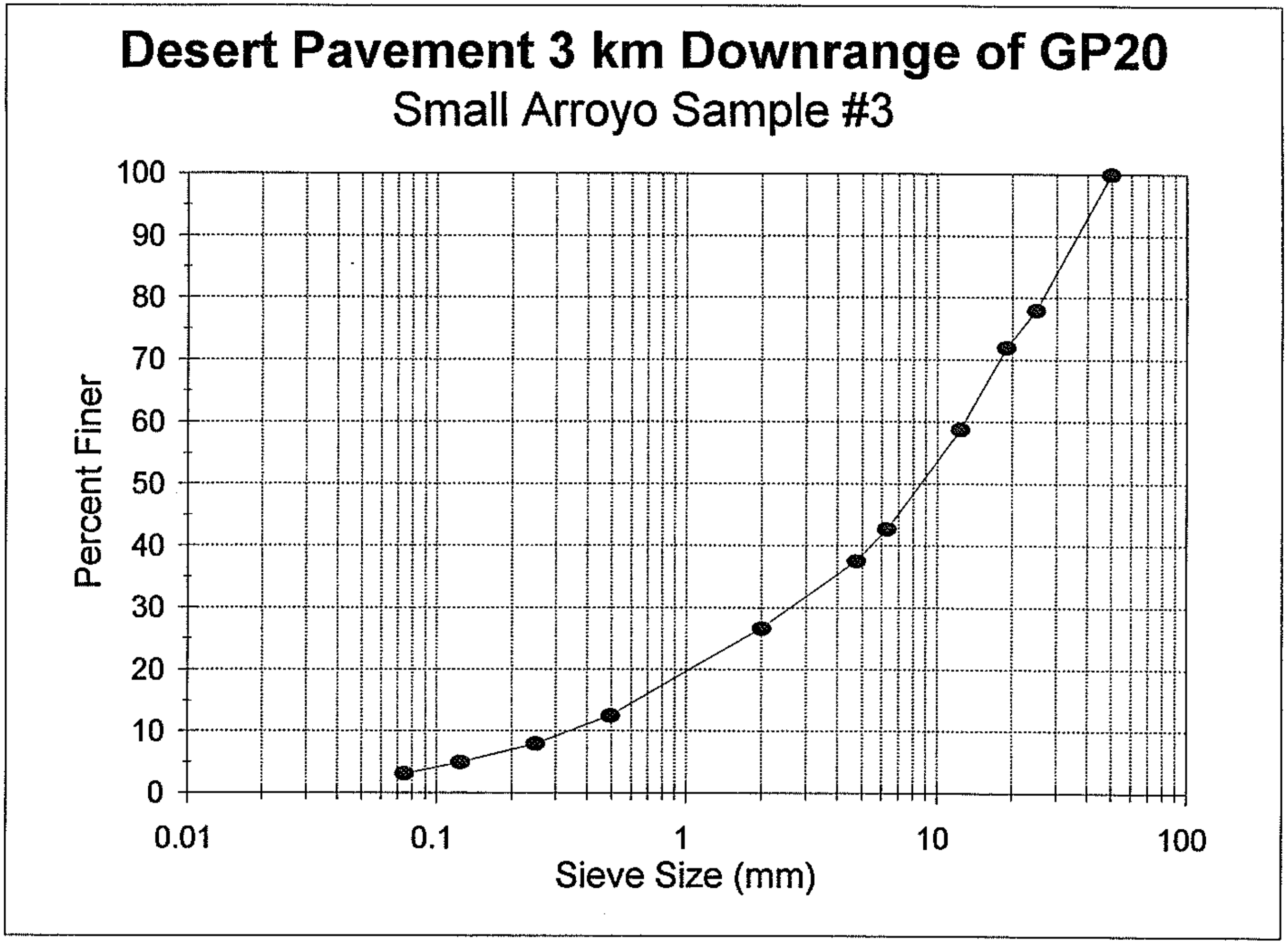
Small Arroyo Sample #1



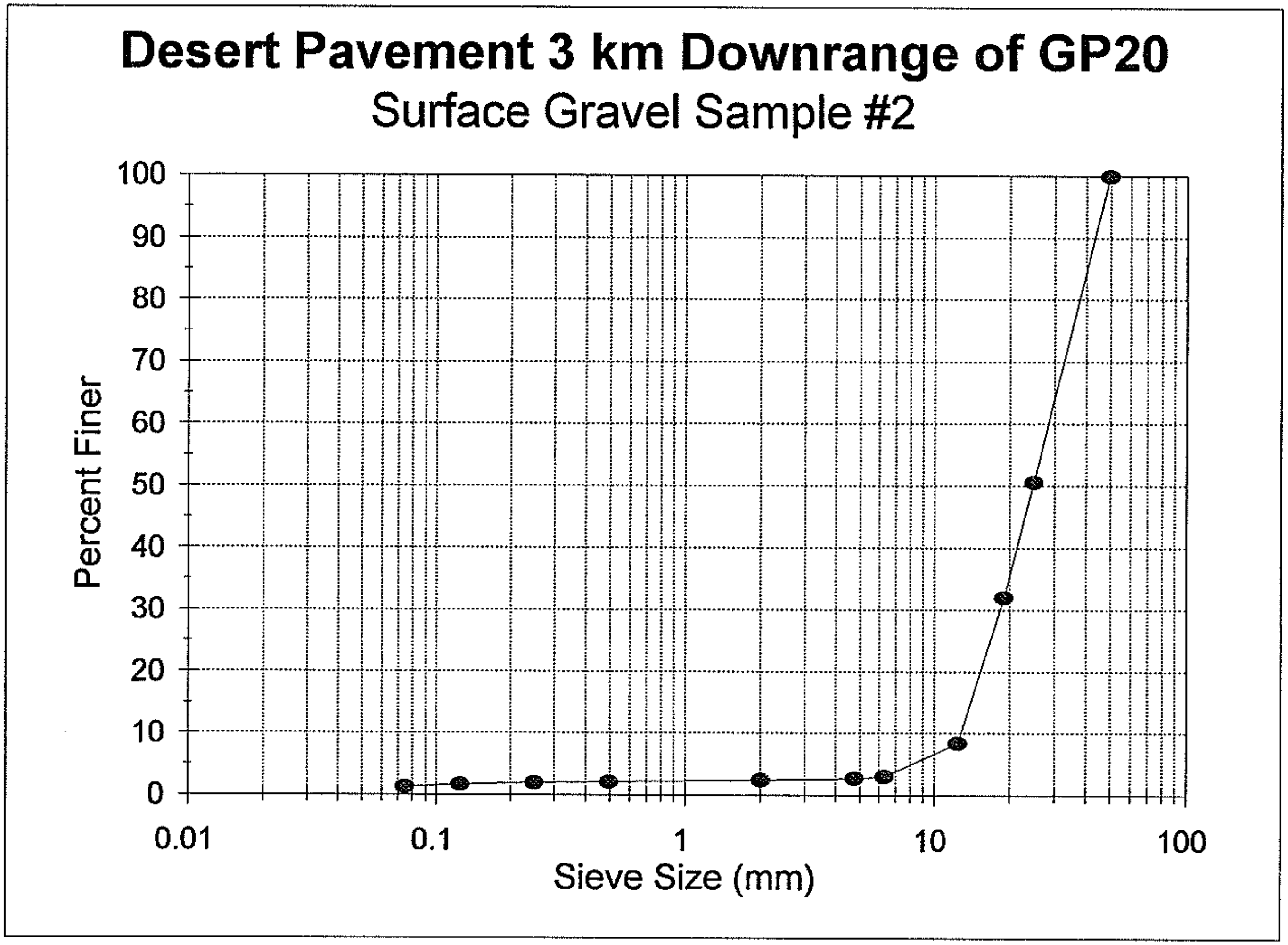
Sieve Size (mm)	Percent Finer (%)
25.000	100.0
19.000	96.1
12.500	88.8
6.300	77.0
4.750	71.5
2.000	54.8
0.500	32.8
0.250	26.0
0.125	18.2
0.075	10.5



Sieve Size (mm)	Percent Finer (%)
50.000	100.0
25.000	78.0
19.000	72.0
12.500	58.9
6.300	42.7
4.750	37.6
2.000	26.7
0.500	12.6
0.250	8.0
0.125	5.0
0.075	3.1
	3



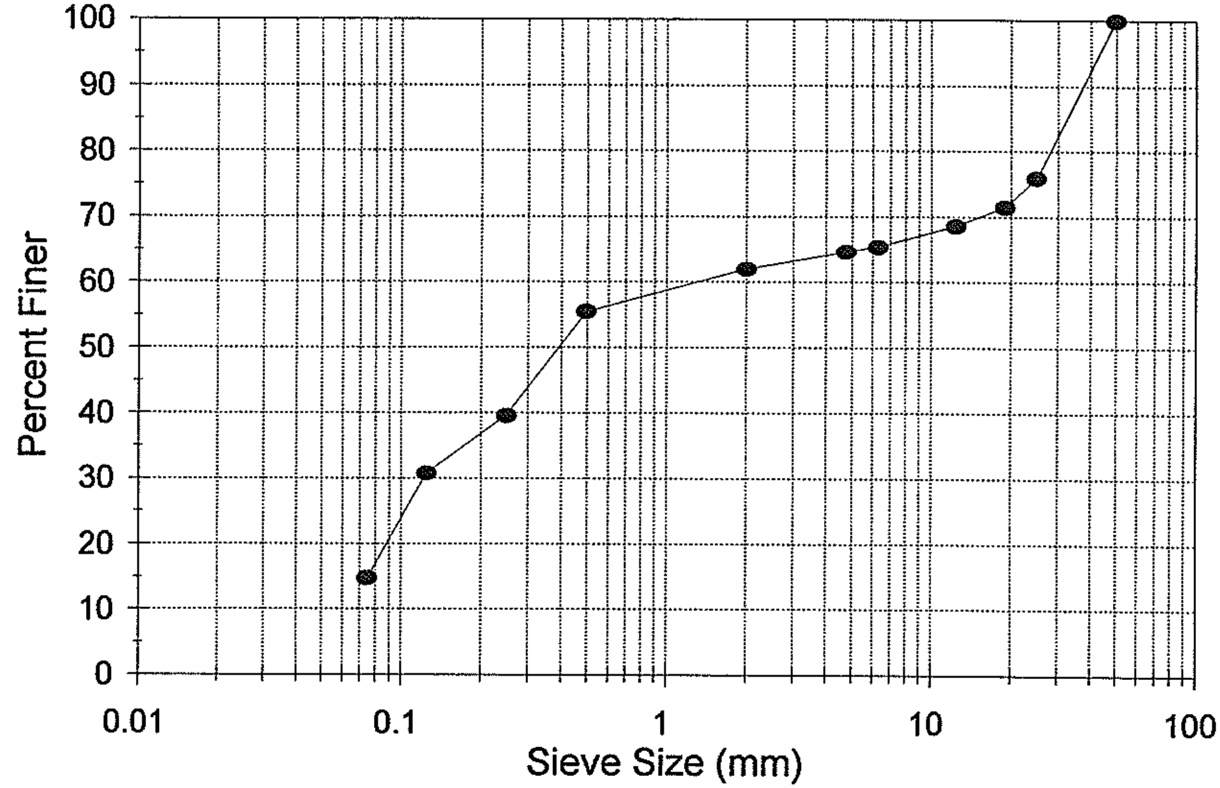
Sieve Size (mm)	Percent Finer (%)
50.000	100.0
25.000	50.7
19.000	32.1
12.500	8.5
6.300	3.0
4.750	2.7
2.000	2.4
0.500	2.1
0.250	2.0
0.125	1.7
0.075	1.3



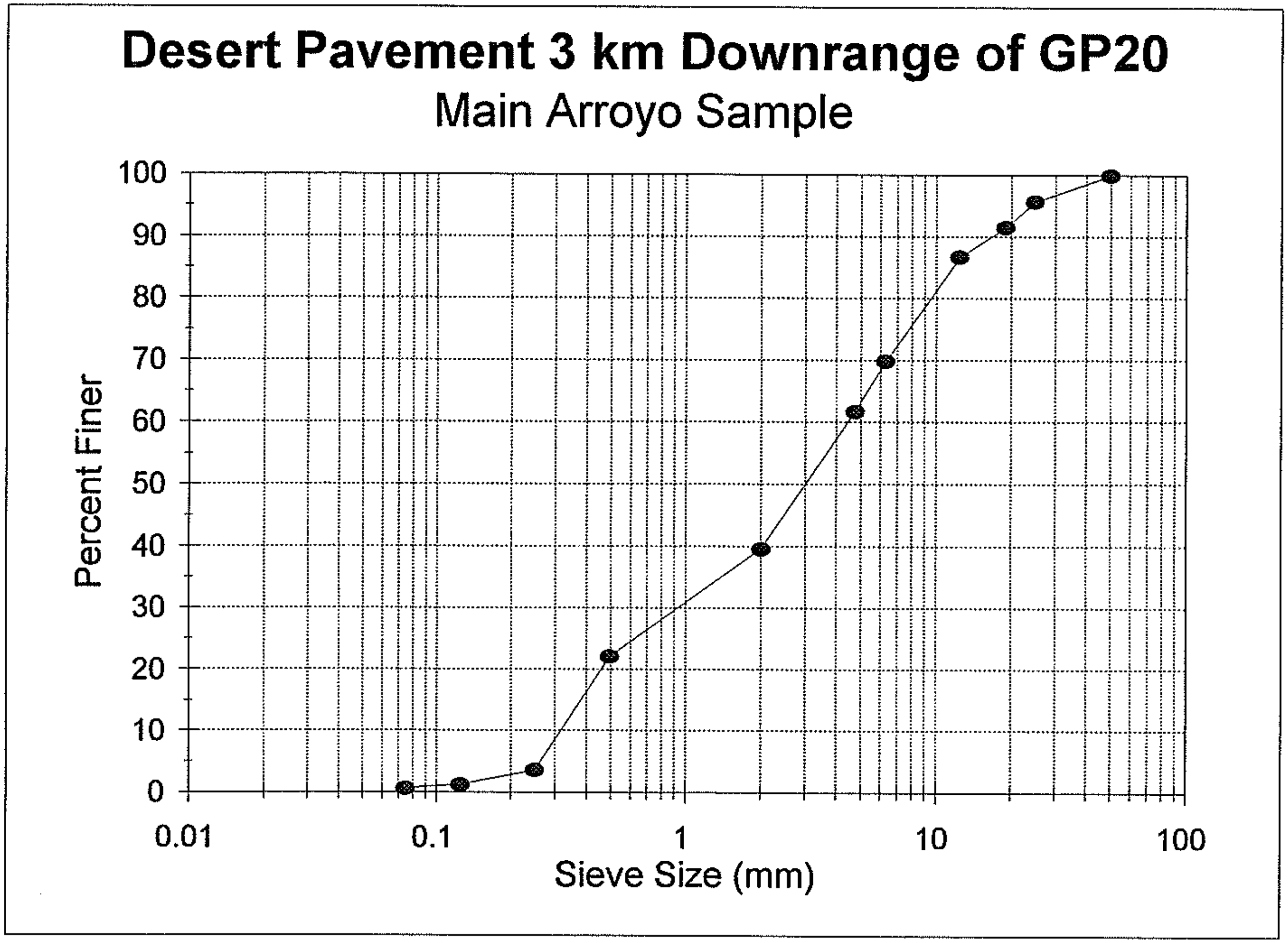
Sieve Size (mm)	Percent Finer (%)
50.000	100.0
25.000	75.9
19.000	71.5
12.500	68.6
6.300	65.4
4.750	64.6
2.000	62.0
0.500	55.5
0.250	39.6
0.125	30.8
0.075	14.8

Desert Pavement 3 km Downrange of GP20

Soil Below Gravel (to 10cm) Sample #2



Sieve Size (mm)	Percent Finer (%)
50.000	100.0
25.000	95.7
19.000	91.5
12.500	86.7
6.300	69.8
4.750	61.7
2.000	39.6
0.500	22.1
0.250	3.6
0.125	1.2
0.075	0.6



Appendix B

Runoff data and Summary Table from experimental runs DU1 through DU9

Test - DU1 (Rainfall only)				
Time	Cummulative Runoff Water		Volume Change	Tare weight of collection barrel
(min)	Weight (lbs)	Liters	Liters	43.0 lbs.
3	66.0	10.4		
5	81.0	17.2	6.8	
7	101.0	26.3	9.1	
9	118.5	34.3	7.9	
11	137.5	42.9	8.6	
13	157.0	51.7	8.8	Avg runoff flow/2min (liters)
15	174.7	59.8	8.0	8.51
17	193.0	68.1	8.3	
19	212.5	76.9	8.8	Avg runoff flow/1min (liters)
21	230.5	85.1	8.2	4.25
23	250.0	93.9	8.8	
25	266.0	101.2	7.3	
27	287.0	110.7	9.5	
29	306.0	119.3	8.6	
29.5				rainfall end
32	313.5	122.7	3.4	runoff end

Test - DU2 (Rainfall only)				
Time	Runoff Water		Volume Change	Tare weight of collection barrel
(min)	Weight (lbs)	Liters	Liters	44.5 lbs.
3	63.0	8.4		
5	81.5	16.8	8.4	
7	100.5	25.4	8.6	
9	118.5	33.6	8.2	
11	137.0	42.0	8.4	
13	155.0	50.1	8.2	Avg runoff flow/2min (liters)
15	174.7	59.1	8.9	8.50
17	193.0	67.4	8.3	
19	211.0	75.5	8.2	Avg runoff flow/1min (liters)
21	230.0	84.2	8.6	4.25
23	249.0	92.8	8.6	
25	267.5	101.2	8.4	
27	287.5	110.3	9.1	
30	312.5	121.6	11.3	rainfall end
32	319.5	124.8	3.2	runoff end

Test - DU3 (Rainfall only)				
Time	Runoff Water		Volume Change	Tare weight of collection barrel
(min)	Weight (lbs)	Liters	Liters	44.5 lbs.
3				
5	105.5	27.7	27.7	
7	110.5	29.9	2.3	
9	135.5	41.3	11.3	
11	155.0	50.1	8.8	Avg runoff flow/2min (liters)
13	171.5	57.6	7.5	1.03
15	192.5	67.2	9.5	
17	211.5	75.8	8.6	Avg runoff flow/1min (liters)
19	230.0	84.2	8.4	0.52
21	251.5	93.9	9.8	
23	270.0	102.3	8.4	
25	288.5	110.7	8.4	
27	307.0	119.1	8.4	
30	330.0	129.5	10.4	rainfall end
31.9	338.7	133.5	3.9	runoff end

Test - DU4 (Overland flow only)				
Time	Runoff Water		Volume Change	Tare weight of collection barrel
(min)	Weight (lbs)	Liters	Liters	44 lbs.
2		15.0		
4	weight	47.0	32.0	
6	not	75.0	28.0	Avg runoff flow/2min (liters)
8	taken	106.0	31.0	29.42
10		134.0	28.0	
12		162.0	28.0	Avg runoff flow/1min (liters)
14		191.5	29.5	14.71
15		206.0	14.5	flow end
17.2		218.0	12.0	runoff end

Test - DU5 (Overland flow only)				
Time	Runoff Water		Volume Change	Tare weight of collection barrel
(min)	Weight (lbs)	Liters	Liters	44.5 lbs.
3	66.0	9.8		
4	83.5	17.7	7.9	
6	119.0	33.8	16.1	Avg runoff flow/2min (liters)
8	153.5	49.5	15.7	16.19
10	189.5	65.8	16.3	
12	226.0	82.4	16.6	Avg runoff flow/1min (liters)
14	262.0	98.7	16.3	8.10
16	297.5	114.8	16.1	
18	332.5	130.7	15.9	
20	369.0	147.2	16.6	flow end
21.4	385.0	154.5	7.3	runoff end

Test - DU6 (Overland flow only)				
Time	Runoff Water		Volume Change	Tare weight of collection barrel
(min)	Weight (lbs)	Liters	Liters	44.5 lbs
1	132.5	48.0		
3	220.0	79.6	31.6	Avg runoff flow/2min (liters)
5	294.5	113.4	33.8	34.00
7	371.5	148.4	34.9	Avg runoff flow/1min (liters)
9	450.0	184.0	35.6	17.00
10	488.0	201.2	17.2	flow end
11.5	525.5	218.2	17.0	runoff end

Test - DU7 (Rainfall + overland flow)				
Time	Runoff Water		Liters	Tare weight of collection barrel
(min)	Weight (lbs)	Liters	Change	44.5 lbs.
2	67.0	10.2		
4	120.5	34.5	24.3	
6	176.0	59.7	25.2	Avg runoff flow/2min (liters)
8	231.0	84.6	25.0	25.11
10	289.0	110.9	26.3	
12	342.5	135.2	24.3	Avg runoff flow/1min (liters)
14	399.0	160.8	25.6	12.55
15				water-off
15.2	452.5	185.1	24.3	runoff end

Test - DU8 (Rainfall + overland flow)				
Time	Runoff Water		Volume Change	Tare weight of collection barrel
(min)	Weight (lbs)	Liters	Liters	44.5 lbs.
2	66.0	9.8		
4	130.0	38.8	29.0	
6	206.0	73.3	34.5	Avg runoff flow/2min (liters)
8	283.0	108.2	34.9	33.01
10	357.0	141.8	33.6	Avg runoff flow/1min (liters)
11	395.0	159.0	17.2	16.50
12				water-off
12.5	493.0	203.5	44.5	runoff end

Test - DU9 (Rainfall + overland flow)				
Time	Runoff Water		Volume Change	Tare weight of collection barrel
(min)	Weight (lbs)	Liters	Liters	44 lbs.
2	70.0	11.8		
4	147.5	47.0	35.2	
6	228.0	83.5	• 36.5	Avg runoff flow/2min (liters)
8	298.5	115.5	32.0	34.86
10	377.0	151.1	35.6	
12	455.0	186.5	35.4	Avg runoff flow/1min (liters)
14	531.0	221.0	34.5	17.43
15				water-off
15.5	611.0	257.3	36.3	runoff end

Summary Table for Experimental Runs

Run #	Type	Outflow Rate (l/m)	Outflow Volume (liters)	Sediment		
				Total Deposits (g)	U in* deposits (g)	Suspended* Sediments (g)
DU1	Rainfall	4.3	122.7	198.92	1.91	126.4
DU2	Rainfall	4.3	121.6	161.98	2.49	8.0
DU3	Rainfall	4.2	129.5	174.85	2.22	27.7
DU4	Overland Flow	14.7	218.0	34.62	0.72	323.9
DU5	Overland Flow	8.1	154.5	none	0.00	10.2
DU6	Overland Flow	17.0	218.2	26.29	0.37	85.1
DU7	Rain+OL Flow	12.6	185.1	135.36	1.60	4.4
DU8	Rain+OL Flow	16.5	203.5	294.00	2.09	22.8
DU9	Rain+OL Flow	17.4	257.2	246.74	2.25	38.6
Total		-	1610.3	1272.96	13.65	647.1

*Calculated from measurements supplied by LANL

Appendix C

Plates (photos) from various stages of the simulation experiments

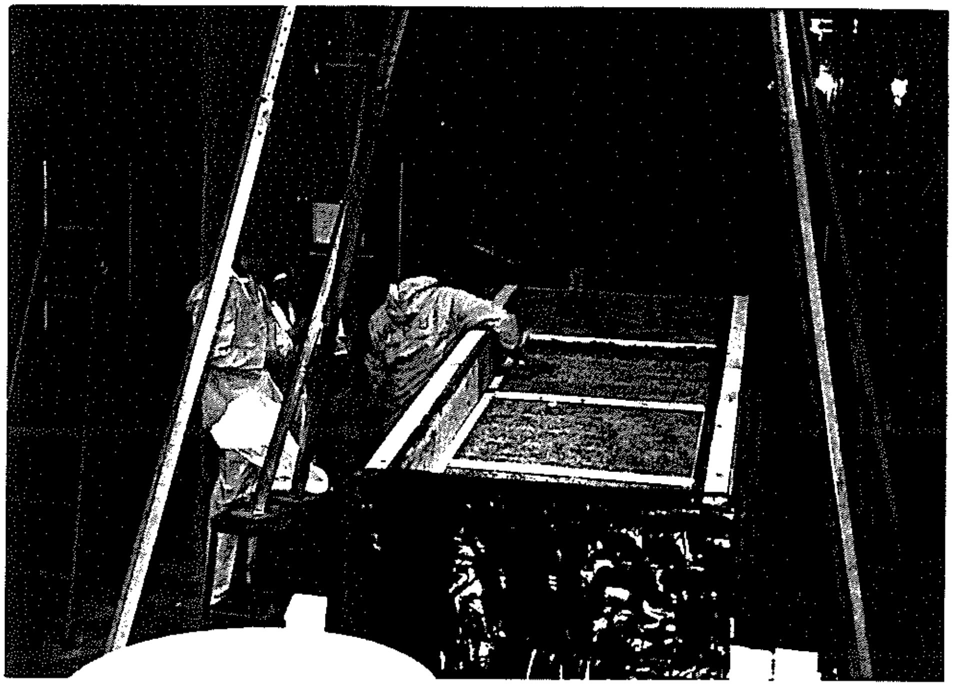


Plate 1. Measurement of grid radioactivity counts prior to experimental runs.

Plate 2. Contaminated soil in simulation soil box at the initiation of first run (DU1).

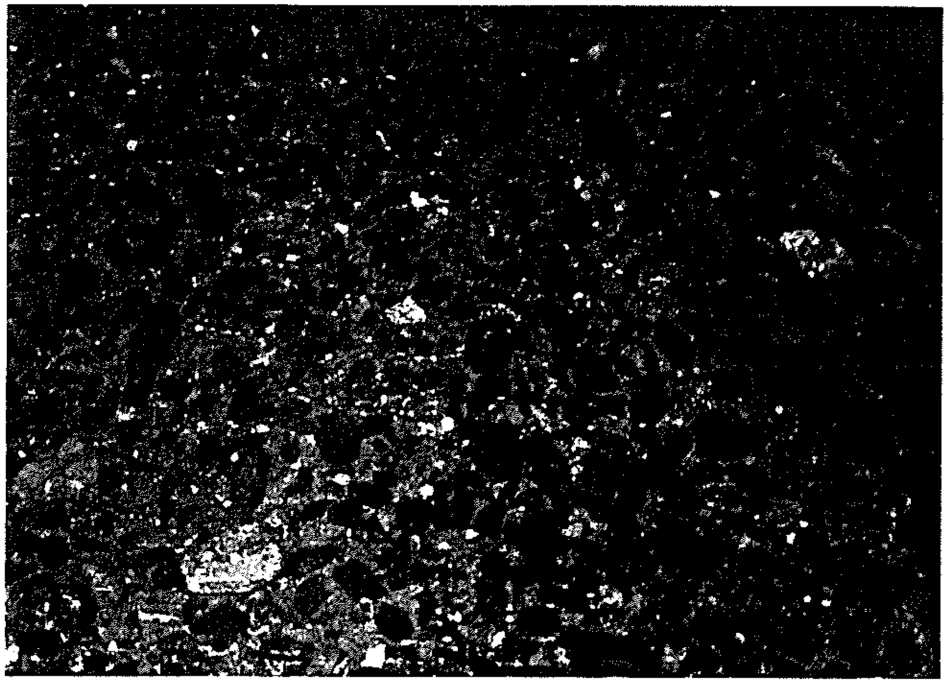


Plate 5. Distribution of depleted Uranium (bright yellow particles) after a simulation run. Desert pavement has a mean size of about 12.5 mm.

Plate 6. Soil and DU exiting simulation box during an overland flow only run.

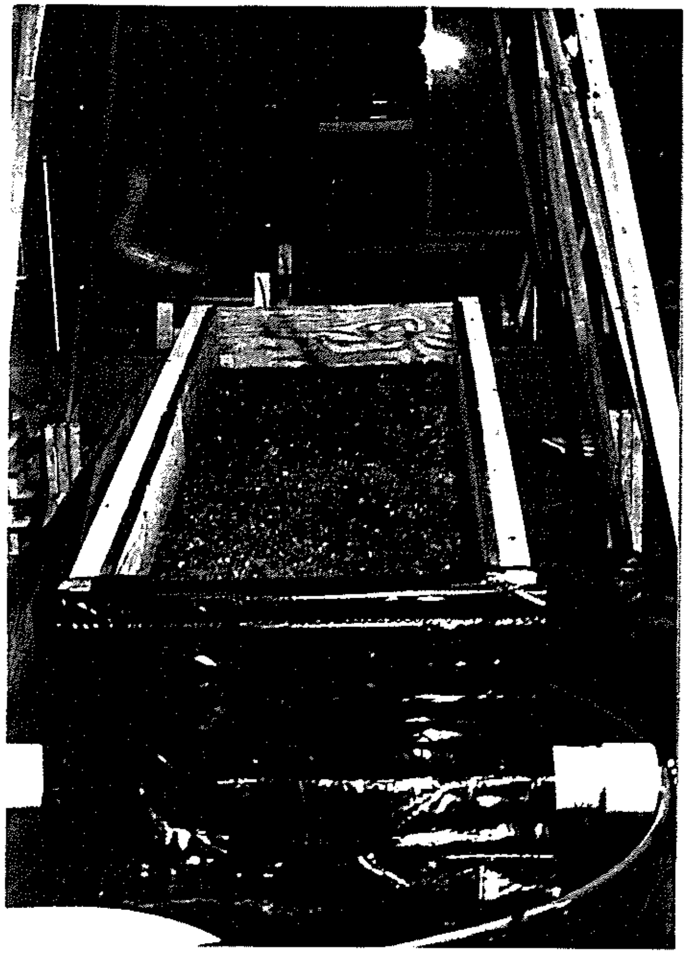


Plate 3. Redistributed soil during run number DU1.

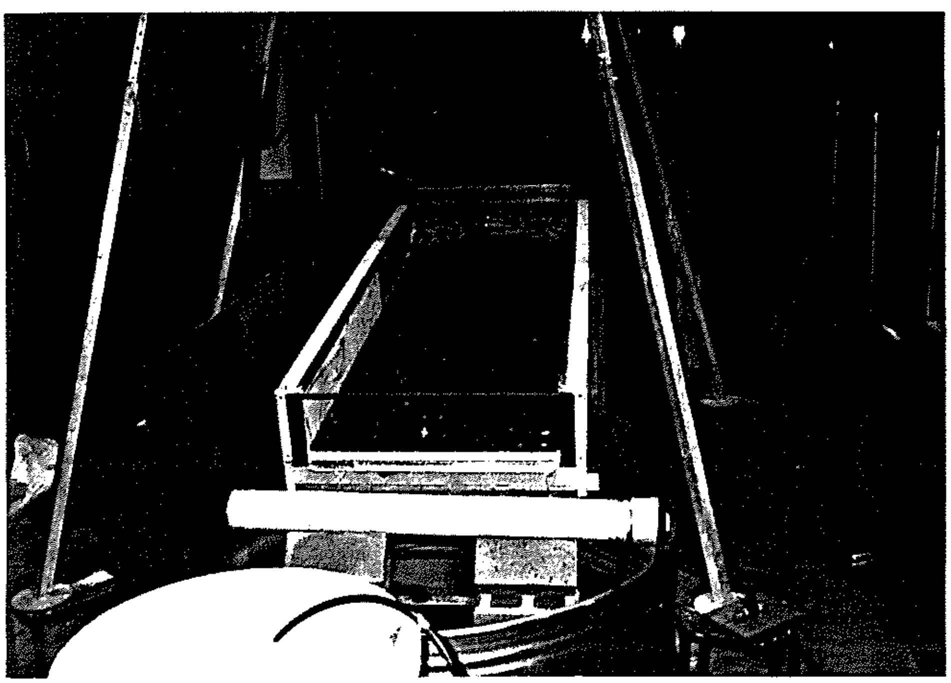
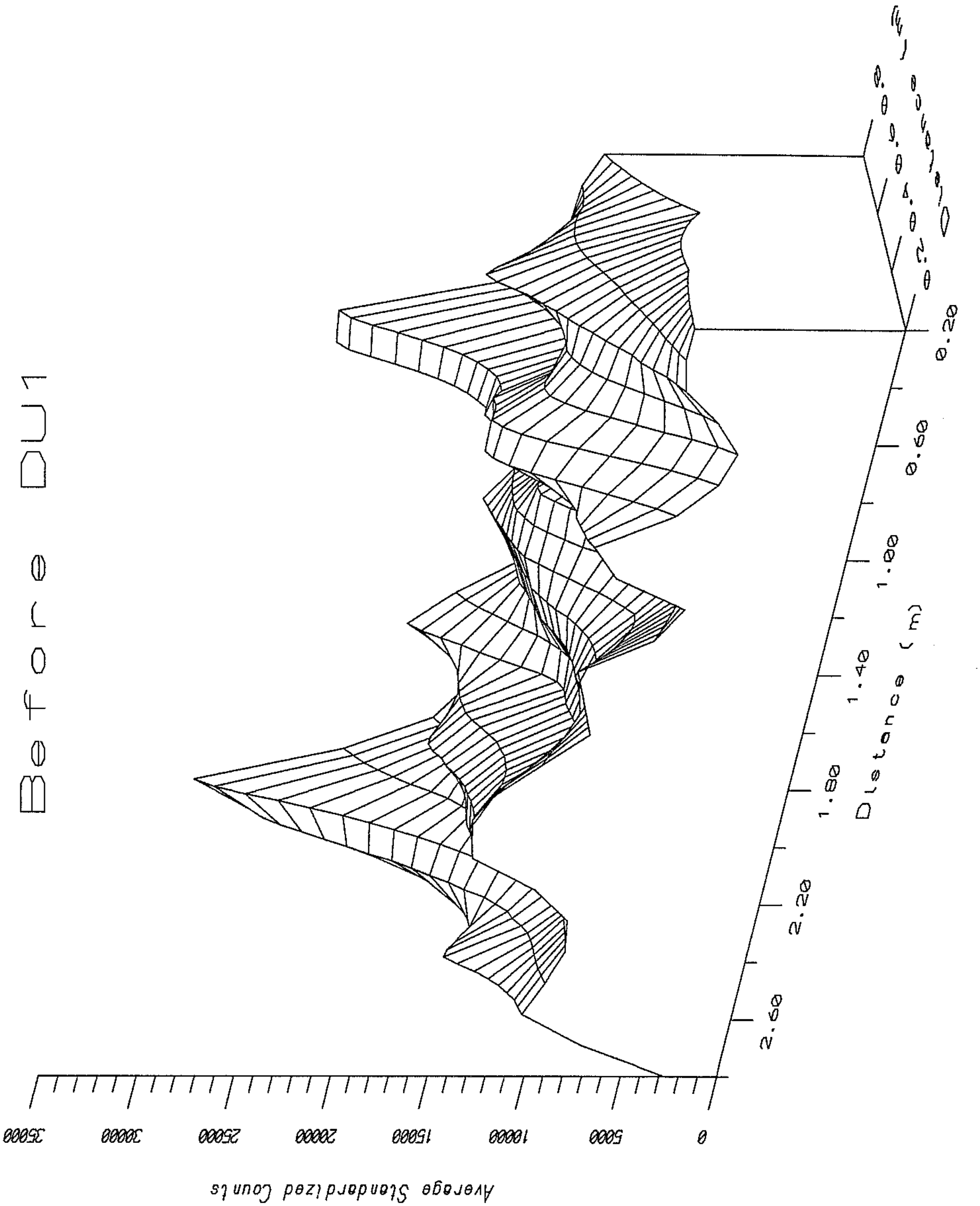
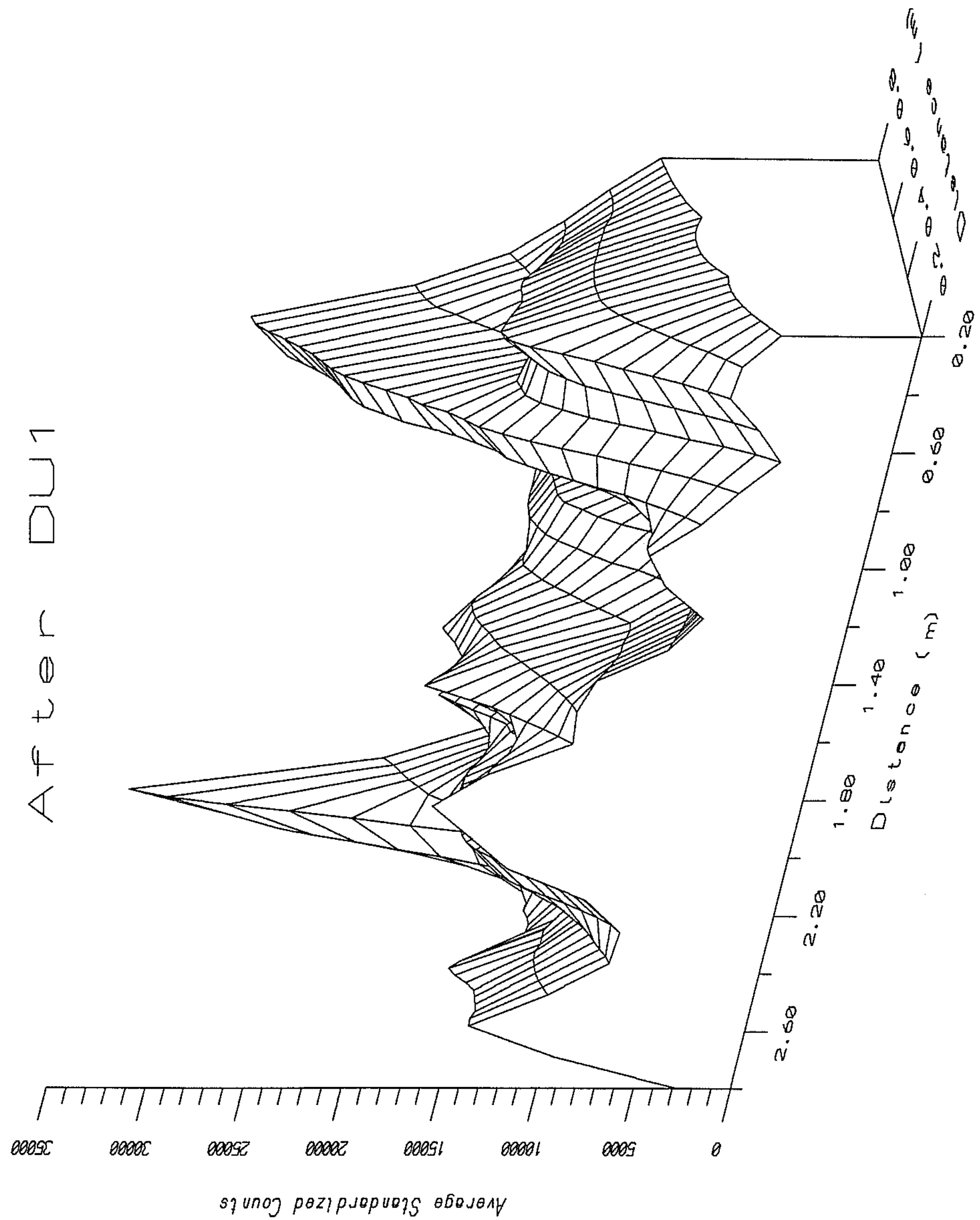


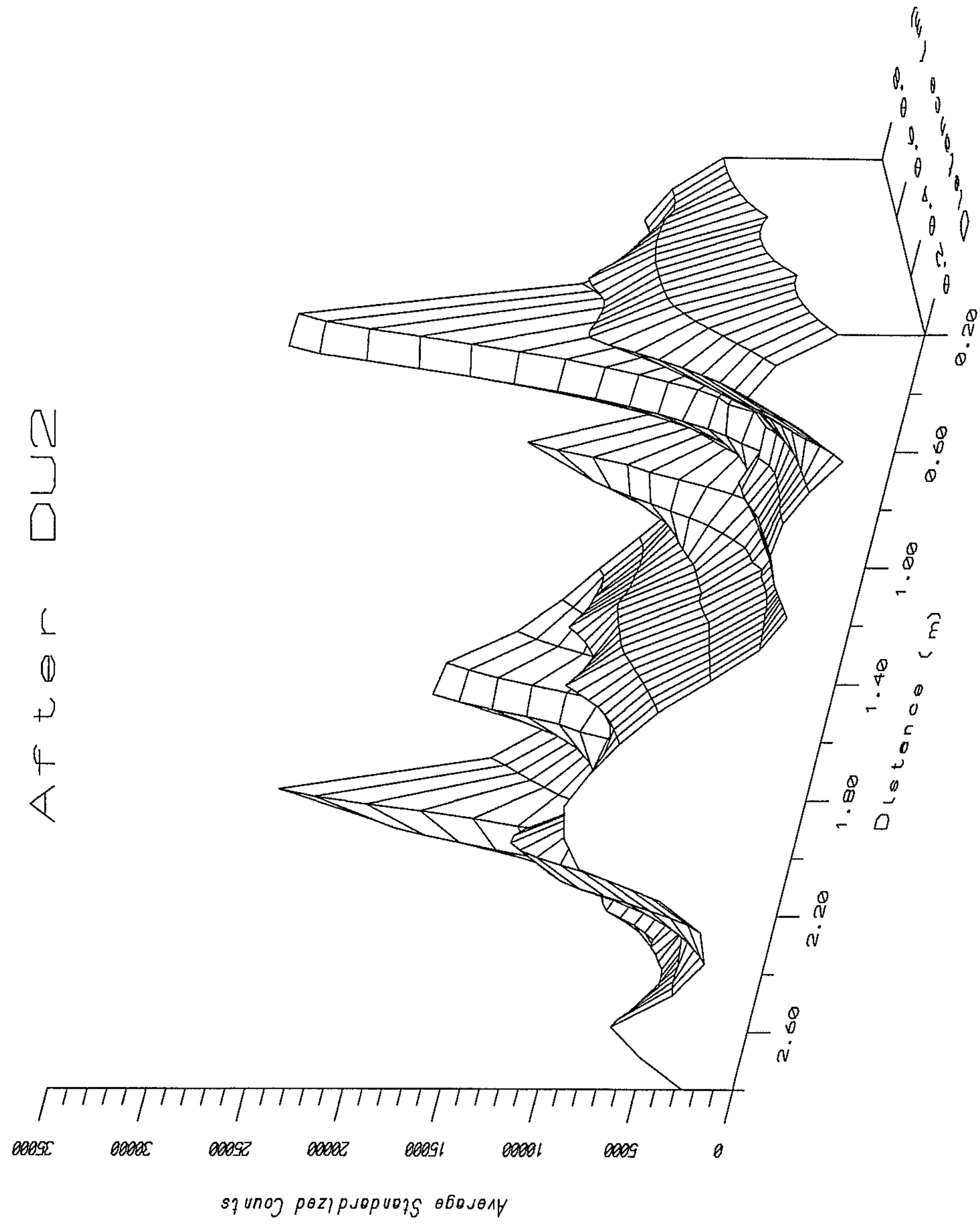
Plate 4. Distribution of depleted Uranium (bright particles) during run number DU4.

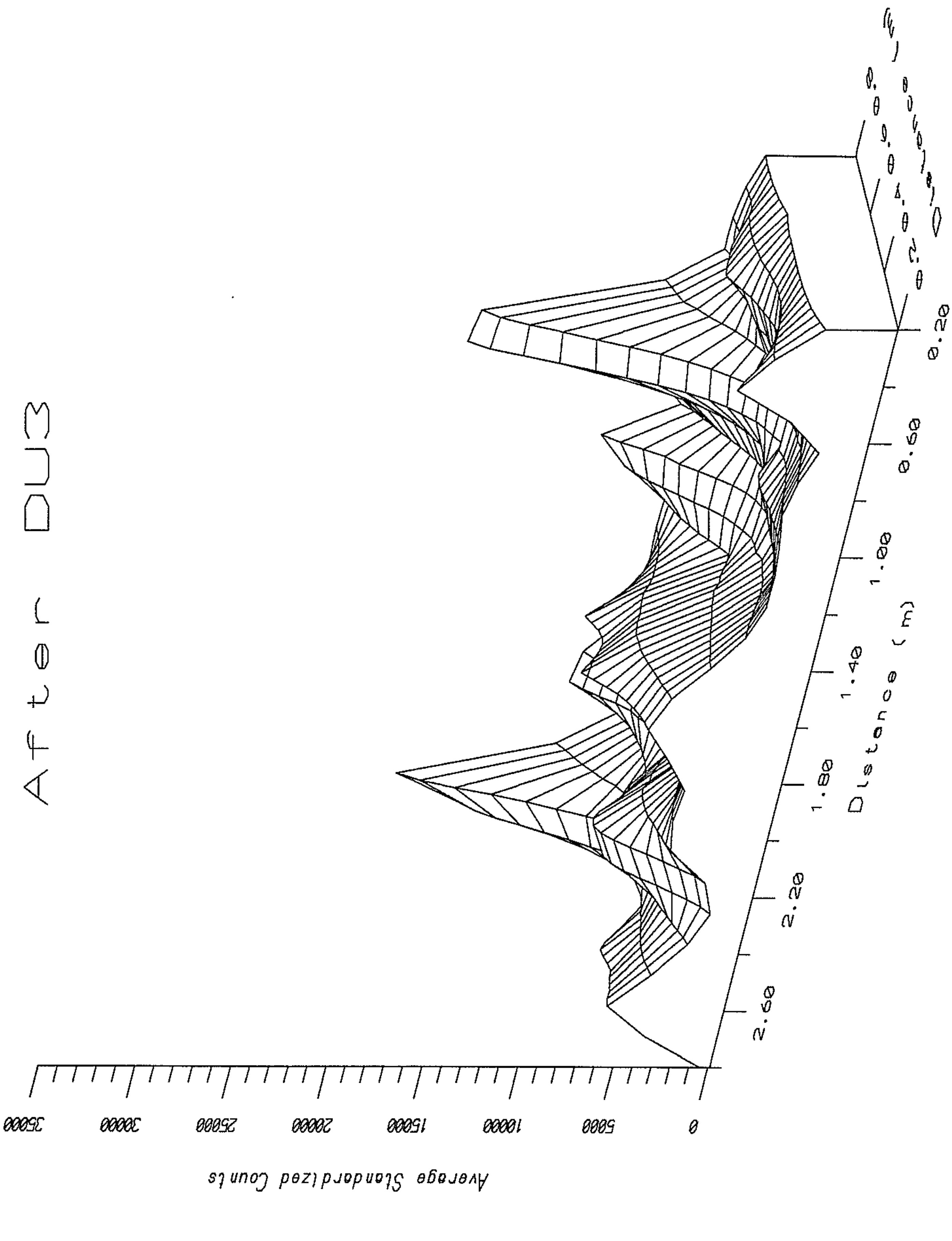
Appendix D

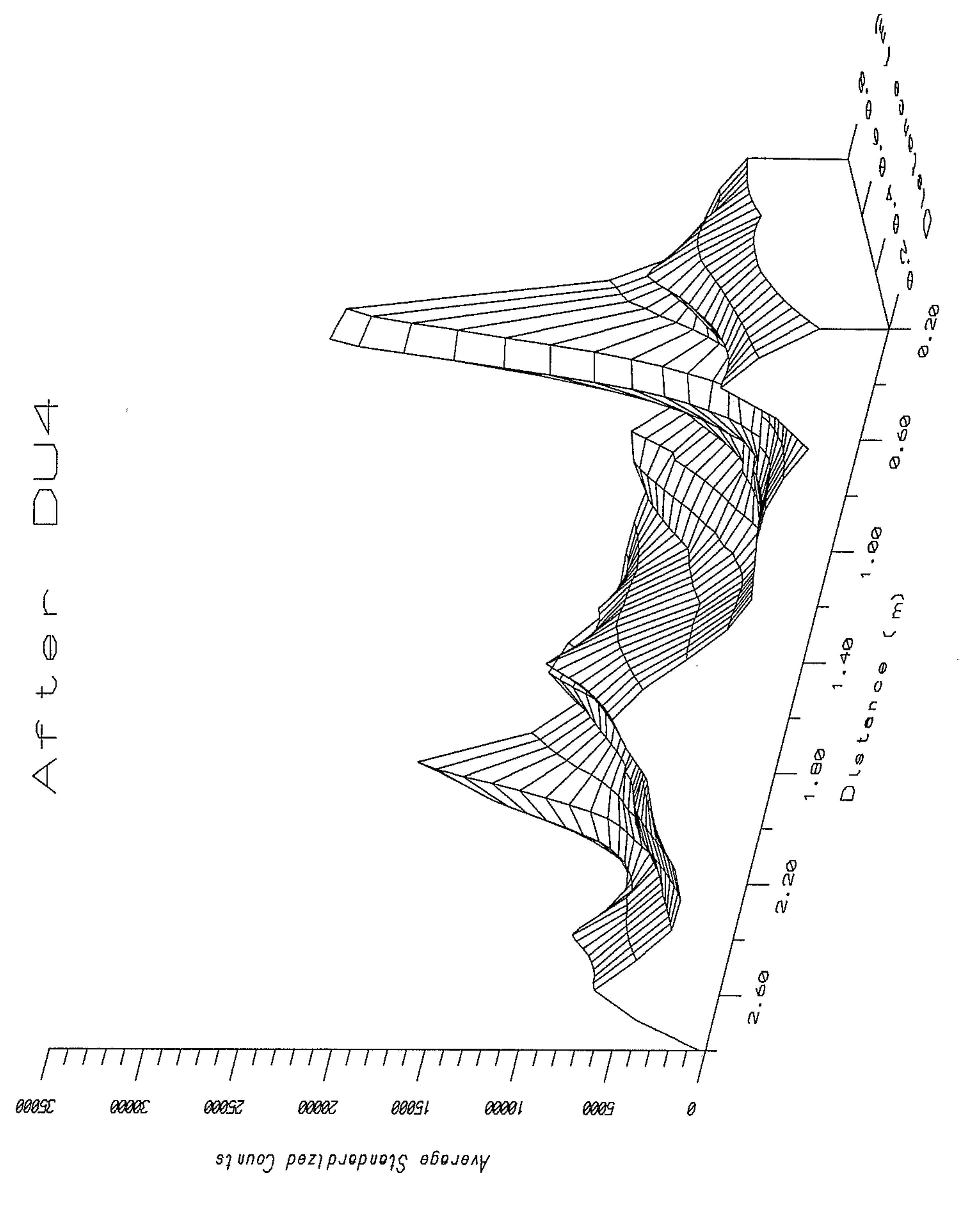
Three-dimensional plots of radioactivity on soil surface: before experiemental runs and after each of the runs DU1 through DU9

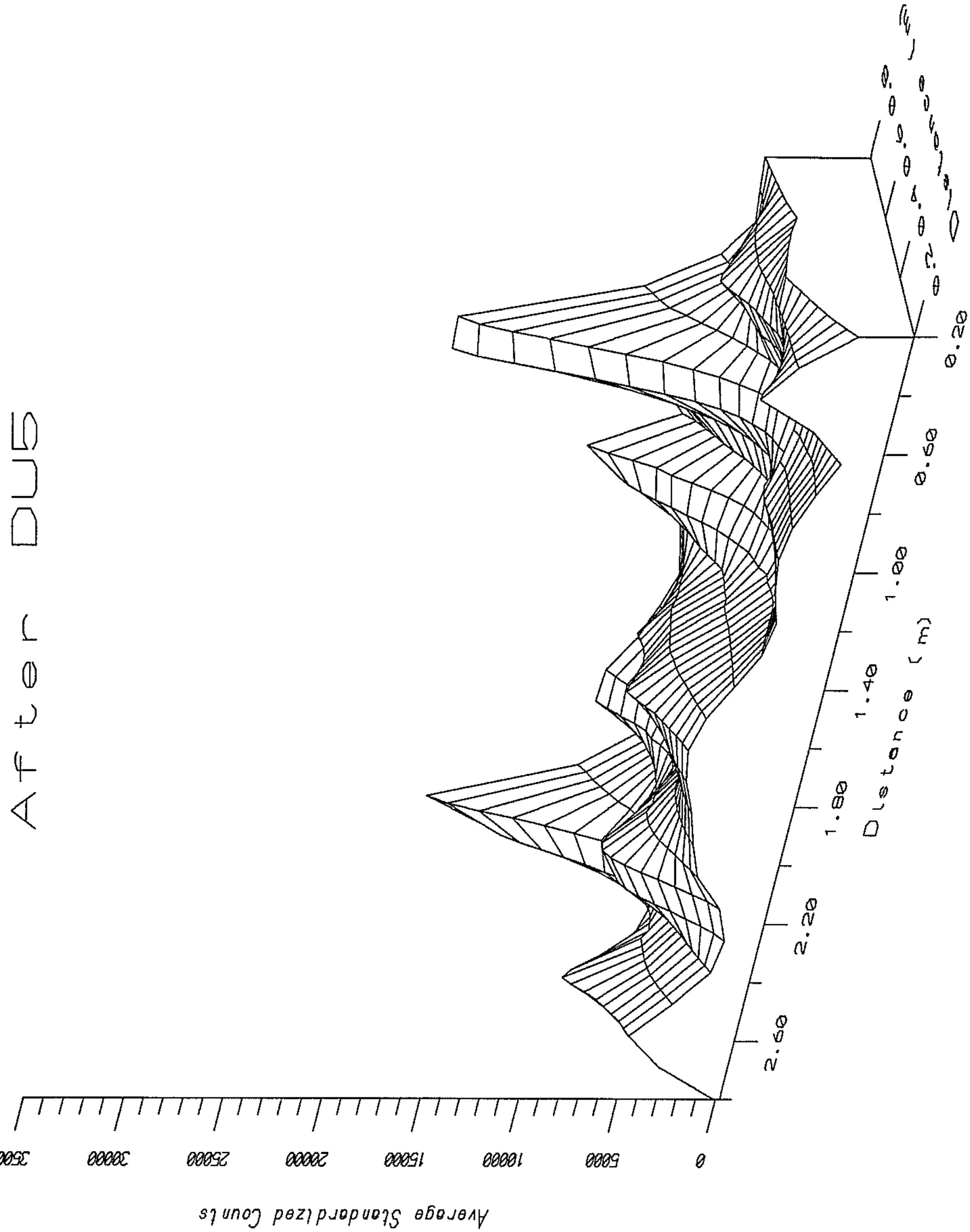

Before DU1
Distance (m)
0.20
0.60
1.00
1.40
1.80
2.20
2.60
Average Standardized Counts
0
5000
10000
15000
20000
25000
30000
35000

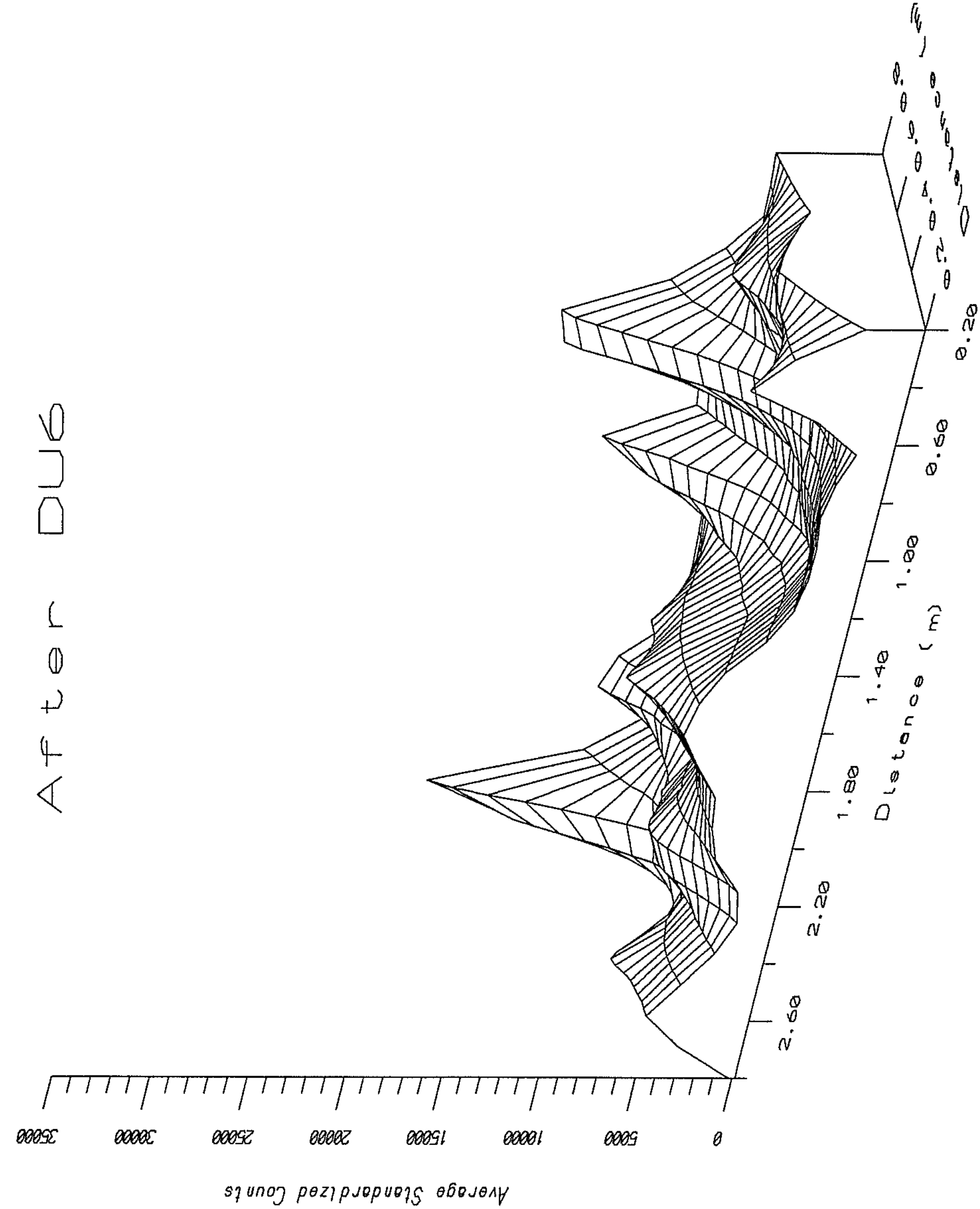

After DU1
Distance (m)
0.20
0.60
1.00
1.40
1.80
2.20
2.60
Average Standardized Counts
0
5000
10000
15000
20000
25000
30000
35000

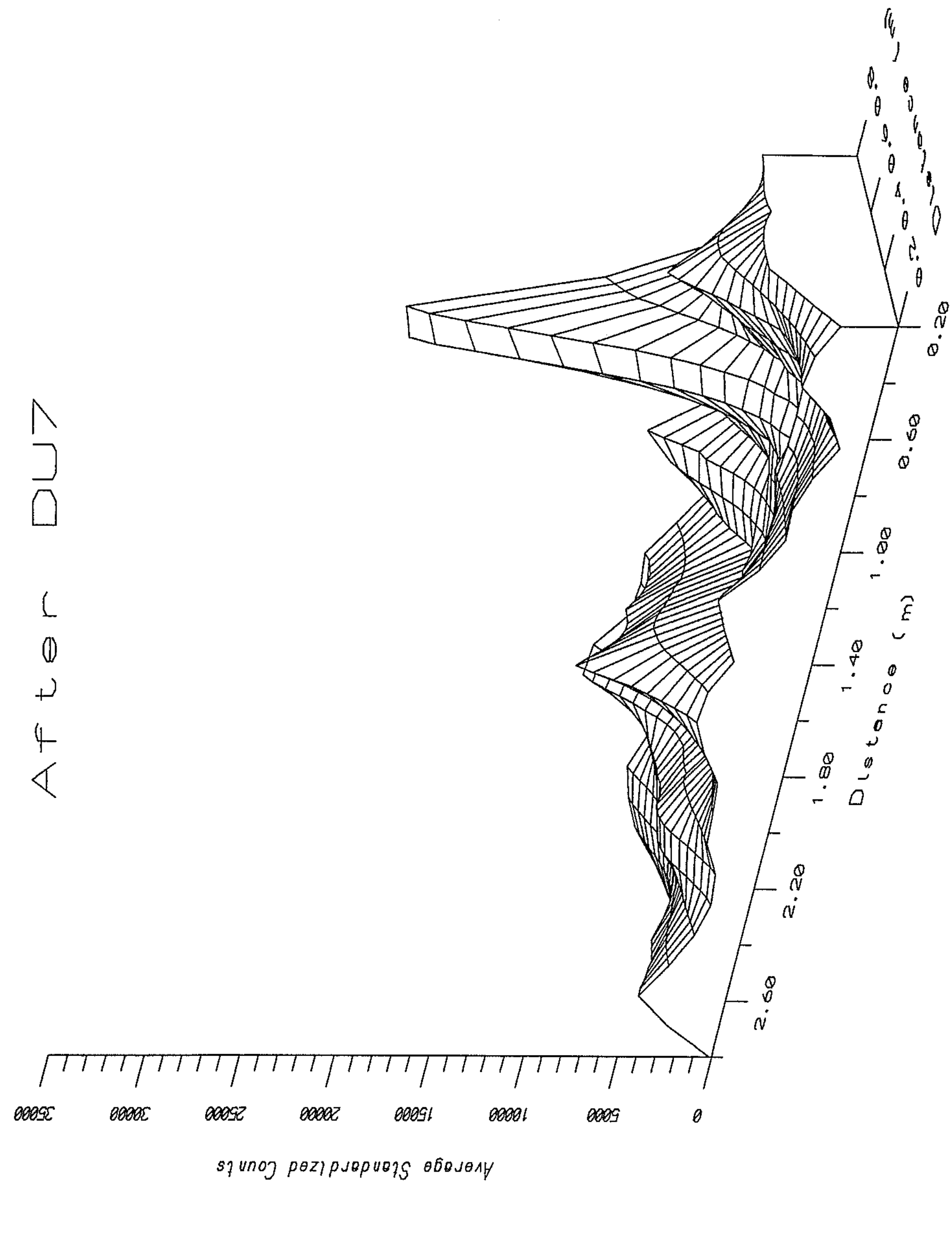

After DU2
Distance (m)
0.20
0.60
1.00
1.40
1.80
2.20
2.60
Average Standardized Counts
0
5000
10000
15000
20000
25000
30000
35000

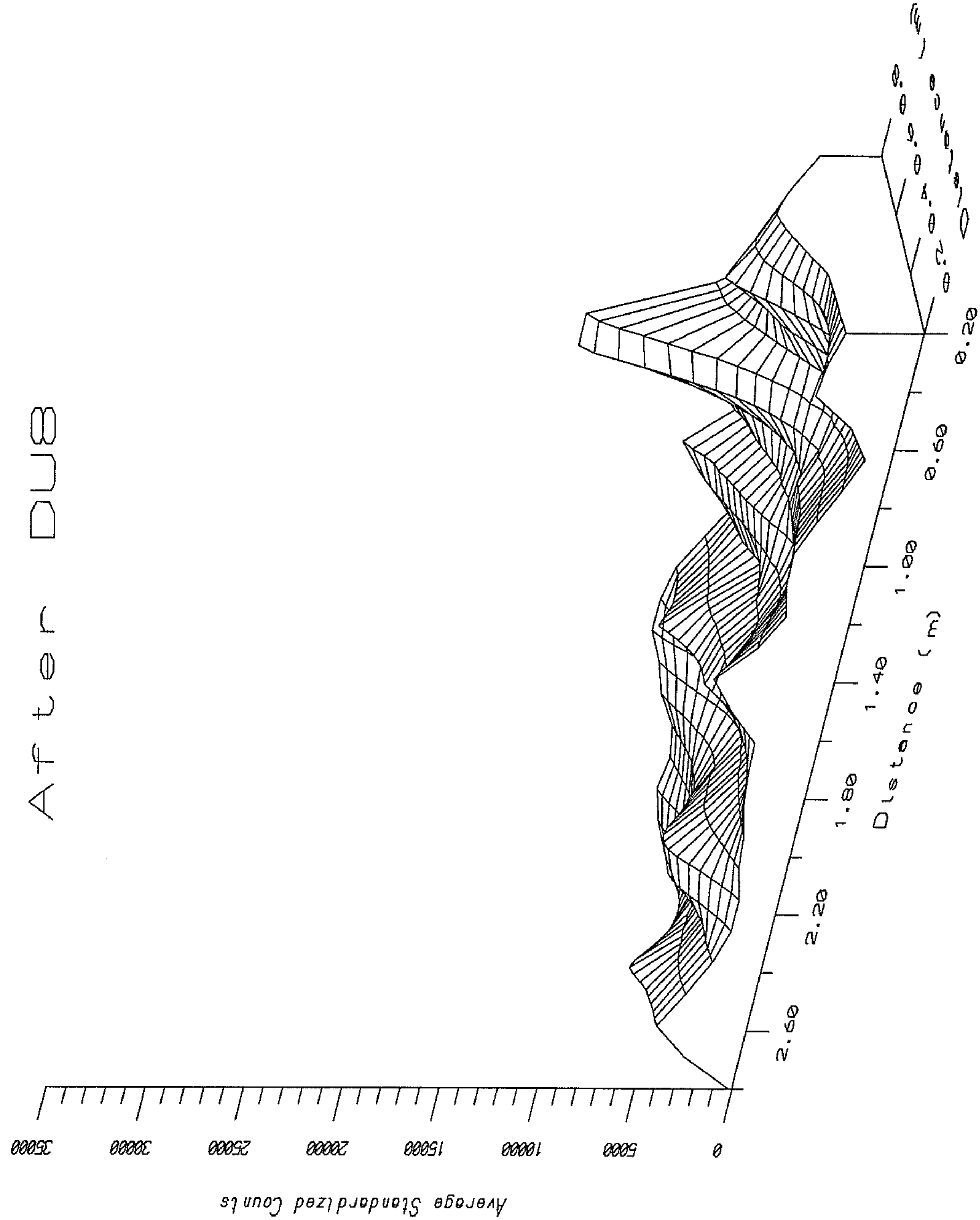

After DU3
Distance (m)
0.20
0.60
1.00
1.40
1.80
2.20
2.60
Average Standardized Counts
0
5000
10000
15000
20000
25000
30000
35000

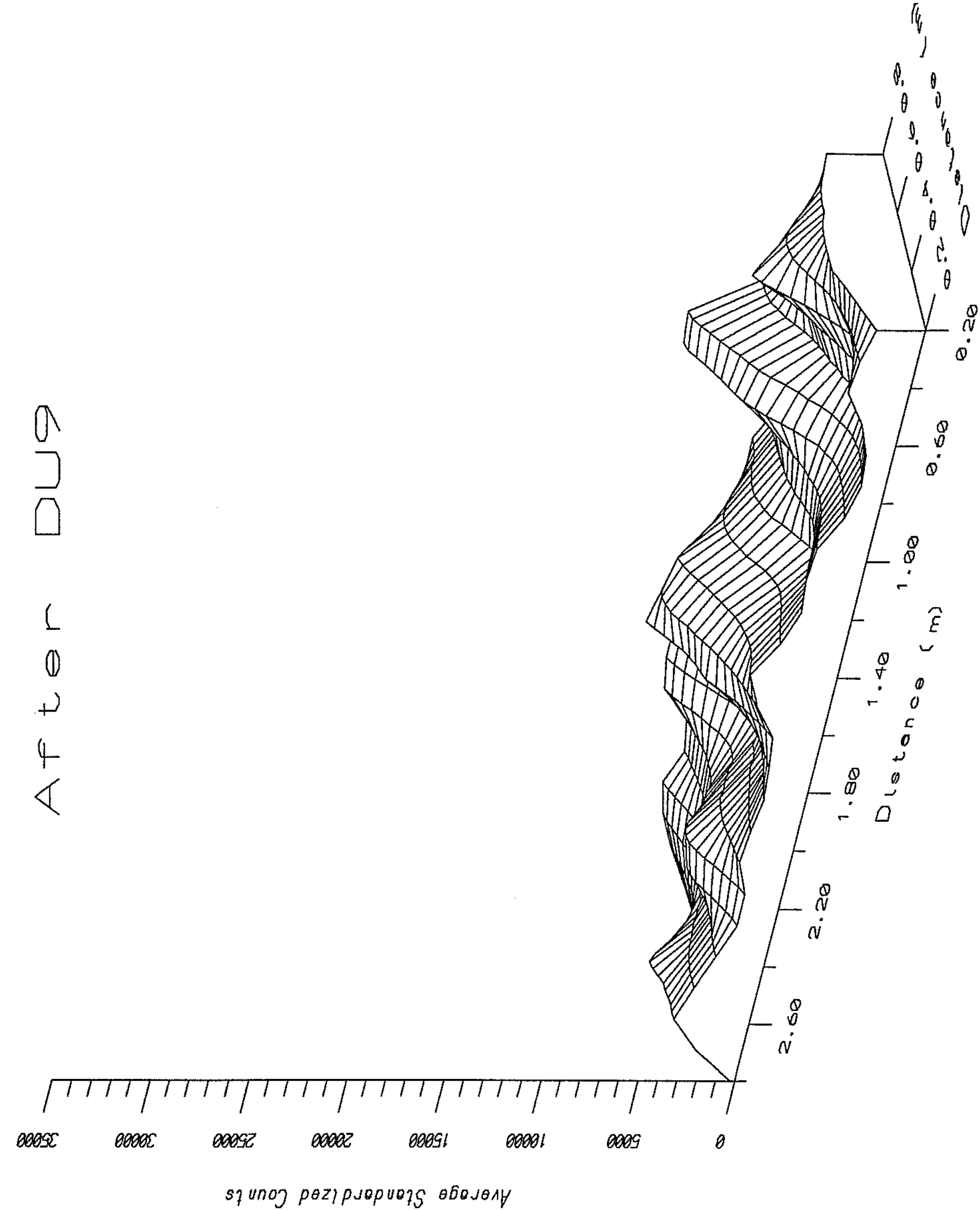

After DU4
Distance (m)
0.20
0.60
1.00
1.40
1.80
2.20
2.60
Average Standardized Counts
0
5000
10000
15000
20000
25000
30000
35000


After DU5
Distance (m)
0.20
0.60
1.00
1.40
1.80
2.20
2.60
Average Standardized Counts
0
5000
10000
15000
20000
25000
30000
35000


After DU6
Average Standardized Counts
0
5000
10000
15000
20000
25000
30000
35000
2.60
2.20
1.80
1.40
1.00
0.60
0.20
Distance (m)
0.2
0.4
0.6
0.8


After DU7
Distance (m)
0.20
0.60
1.00
1.40
1.80
2.20
2.60
Average Standardized Counts
0
5000
10000
15000
20000
25000
30000
35000


After DUB
Distance (m)
0.20
0.60
1.00
1.40
1.80
2.20
2.60
Average Standardized Counts
0
5000
10000
15000
20000
25000
30000
35000



After DU9
Distance (m)
0.20
0.60
1.00
1.40
1.80
2.20
2.60
Average Standardized Counts
0
5000
10000
15000
20000
25000
30000
35000

Appendix E

Data and calculations for determining overland flow resistance (Manning's 'n)

Manning's n Calculations

Run #	Volume between Ts andTf (L)	Mean Q at Ts (L/min)	Tf-Ts (min:sec)	Ys (m)	V (m/sec)	Manning's n
DU1	1.1	4.25	2:26	0.00037	0.193	0.0086
DU2	3.2	4.25	1:59	0.00107	0.066	0.0510
DU3	4.0	4.16	1:53	0.00133	0.052	0.0756
DU4	11.8	14.71	2:10	0.00393	0.062	0.1297
DU5	7.3	8.10	1:25	0.00243	0.055	0.1058
DU6	17.0	17.00	1:30	0.00567	0.050	0.2063
DU7	11.7	12.55	0:20	0.00390	0.054	0.1499
DU8	12.7	16.50	0:30	0.00423	0.065	0.1307
DU9	18.9	17.48	0:30	0.00630	0.046	0.2394
*RT1	3.8	4.40	1:52	0.00125	0.059	0.0642
*OT1	6.6	8.25	2:37	0.00219	0.063	0.0873
*OT2	7.0	8.03	2:55	0.00232	0.058	0.0984
*OT3	7.2	8.25	2:53	0.00238	0.058	0.1003
*CT1	8.6	11.63	3:50	0.00287	0.068	0.0968

Ts = Time at rainfall or applied flow stoppage
Tf = Time at cessation of flow from plot
Ys = Calculated depth of flow at Ts
v = Velocity of flow at Ts
s = 0.107

$$n=\frac{Ys^{2/3}S^{1/2}}{v}$$

* Runs made before contaminated soil was applied in order to "season" the plot

RT1 = Pre-rainfall test #1
OT1 = Pre-overland flow test #1
OT2 = Pre-overland flow test #2
OT3 = Pre-overland flow test #3
CT1 = Pre-combined (rainfall + overland flow) test #1