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Animal Intrusion Studies for Protective Barriers: Status Report for FY 1988

L. L. Cadwell, Task Leader
L. E. Eberhardt
M. A. Simmons

May 1989

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
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Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

The objective of the Biointrusion Control Task is to provide technical support to Westinghouse Hanford Company's Protective Barrier Development Program for evaluating and predicting potential impacts of animal burrowing on long-term barrier performance. This document reviews the major accomplishments for FY 1988, which is the initial year of the work. The scope of work includes a literature review, field studies, and modeling to assess burrowing impacts as they may contribute to increased infiltration of surface water through barriers, increased quantities of soil available for erosion because of surface soil disturbance, and direct physical transport of contaminants to the surface.

Key findings for FY1988 are listed below.

- Large mammal burrows were characterized in terms of size, depth, and orientation of excavated castings. Most soil castings were deposited on the down-slope edge of the hole, which could serve as a dam for runoff and direct water into the burrows.

- Measurements made in late spring indicated that soil moisture beneath and around large mammal holes was actually drier than for nearby control sites.

- Conductivity probes were evaluated for determining changes in soil moisture beneath large mammal burrows and were found to be unsuitable. Neutron probes were selected to monitor soil mositure changes below the burrows.

- Preliminary field studies indicated that high-intensity rainfall can enter large mammal burrows from three sources: 1) direct entry of incident rainfall, 2) runoff from microwatersheds created by soil cast to the surface by animals during digging, and 3) upslope runoff that flows into burrow openings.

- Observations showed deep water penetration below large mammal burrows subsequent to a late May natural rainfall event that occurred on the Upper Snively field site.

- High-intensity simulated rainfall penetrated to greater depths below large mammal burrows than in control locations.

- The literature was reviewed for information on burrowing characteristics of eight mammal and invertebrate species that occur on the Hanford Site or in similar western habitats.

- The literature review revealed that little or no information is available on most burrowing characteristics for the badger (Taxidea taxus), marmot (Marmota flaviventris), and harvester ant (Pogonomyrmex owyheei).

- Aspects of animal burrowing that are poorly documented for the reviewed species included number of burrows constructed per individual animal, amount of soil displaced during burrow construction, and lifetime and fate of burrows once they are constructed.

- Fieldwork was initiated on fate and lifetime of burrows for abundant Hanford species, including Great Basin pocket mice (Perognathus parvus),Townsend's ground squirrels (Spermophilus townsendii), and deer mice (Peromyscus maniculatus). One hundred and sixty-nine active ground squirrel burrow entrances and 213 mouse burrow entrances were marked and monitored.

- An existing computer code (BIOPORT) was reviewed and evaluated for use in predicting the impact of long-term animal burrowing on protective barriers.

- The BIOPORT code needs to be expanded to more realistically model animal burrowing dynamics.

- Work was begun on expanding the code. Modifications made include adding parameters for colonization rate, burrow reuse, burrow collapse based on burrow age, and succession of animal species over time.

ACKNOWLEDGMENTS

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P. B. Test, C. K. Russell, N. V. Marr, M. J. Harris, D. R. Newcomer, and M. E. Thiede provided field assistance. M. D. Campbell designed and produced the conductivity probes. W. J. Waugh reviewed an initial draft of this report. G. P. O'Connor provided editorial assistance.

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INTRODUCTION

Protective barriers have been identified as fundamental components for providing long-term isolation of certain Hanford defense wastes disposed of near-surface (DOE 1987). A program is being conducted that addresses barrier performance standards, technology development, and design (Wing 1988). The program objectives are to design a barrier that will be functional for an extended design life of 10,000 years. The purpose of barriers is to prevent, to the extent possible, migration of contaminants to groundwater. Thus, intrusion by man or the natural biota, erosion or loss of the barrier, and infiltration of surface water are major design considerations.

A series of tasks have been initiated by Pacific Northwest Laboratory (PNL) through Westinghouse Hanford Company to address protective barrier and warning marker system development (Wing 1988). The objective of PNL's Biointrusion Control Task is to provide information for evaluating and predicting potential impacts of animal burrowing on long-term barrier performance. The purpose and scope of work under this task are based on Landeen et al. 1987. PNL initiated work on three subtasks in FY 1988: Task A - water infiltration in response to large mammal burrowing, Task B - animal burrow characteristics, and Task D - prediction and integration.

The water infiltration in response to large mammal burrowing subtask is directed at defining and quantifying the extent to which large animal burrows may influence the penetration of surface water (precipitation) through the barrier. This fiscal year, criteria for locating a study area were established, a suitable location was found, large mammal burrows at the study site were characterized, preliminary field studies were conducted, and measurements were made on the penetration of water into burrows in response to both natural and simulated high-intensity rainfall.

The animal burrow characteristics subtask is directed at defining and quantifying important animal burrow parameters for use in predictive model(s). Literature was reviewed to determine what type of data were available. Field studies were initiated to determine the lifetime and fate of burrow systems for some important Hanford Site mammals.

The prediction and integration subtask is directed at selecting, adaptating, and applying an appropriate model that can be used to predict burrowing as it may influence water infiltration, surface soil erosion, and contaminant transport. Limited work was done in model review to ensure that field study results would be coordinated with anticipated model requirements. Work was also initiated to identify model output requirements not met by an existing code and to modify the model.

This report describes the activities conducted under the three subtasks. Water infiltration in response to large mammal burrowing is discussed in the following section. Animal burrow characteristics and prediction and integration are described in subsequent sections.

WATER INFILTRATION IN RESPONSE TO LARGE MAMMAL BURROWING (TASK A, SUBTASK 2)

Large burrowing mammals, particularly the badger (Taxidea taxus) and coyote (Canis latrans), are abundant on the Hanford Site. These mammals have significant potential for impacting water infiltration because they dig numerous large burrows in search of prey. Observations made during recent rainfall simulation experiments at Hanford suggest that soil deposited near burrow entrances can serve as dams that funnel water into the burrows. The objective of this subtask is to determine water infiltration response relative to large mammal burrowing. The approach is to conduct measurements of soil moisture changes near large mammal burrows in fine-textured soils that are similar to those under consideration for use on protective barriers. This study is designed to make measurements subsequent to natural and simulated high-intensity rainfall.

STUDY AREA

Soils on the Hanford Site range from fine particle-dominated silt loams to coarser textured sands. In comparison to the silt loam soils, the sandy soils are susceptible to wind erosion, have limited moisture holding capacity, typically support a relatively meager vegetation growth, and are generally less attractive to burrowing mammals. The ability of the finer-textured soils to store seasonal precipitation until the plant community is able to return it to the atmosphere via transpiration is the primary reason that soils dominated by fines are desirable for covering protective barriers. Last et al. (1987) reported that the fine-textured soils being considered for use on protective barriers have greater than 30% fines and moderate to high water storage capacity. Characteristics that make fine-textured soils desirable for use on protective barriers also make them attractive to burrowing animals. For example, fine-textured Hanford soils have sufficient physical structure to permit animals to construct burrows that do not collapse, and because these soils also support a greater vegetative cover than sandy soils, a food base is available for a variety of animal species.

Criteria for selecting a study site to determine the effects of large mammal burrowing on surface water infiltration included: 1) generally fine-textured soils, 2) a relative abundance of digging activity, and 3) a nearby source of water that could be used for simulating rainfall.

We used a Hanford Site map to identify areas known to have fine-textured soils that were located near sources of water (primarily springs and streams). Our experience indicated that the soil cast to the surface by large burrowing or digging mammals remains conspicuous for some time and can be seen from the air. During February 1988, we flew in a small fixed-wing aircraft at low altitude over areas identified on maps to help locate a study site that met our requirements. We identified four potential study sites, Cold Creek vicinity (approximately 5 km west of the Yakima Barricade), Bobcat Canyon alluvium (about 5 km south of gate 117), Lower Snively old field (approximately 6 km southwest of gate 118), and Upper Snively old field (4 km south of the Lower Snively old field) (Figure 1). Inspection from the ground showed that the Upper Snively old field was best suited for study. The site has a fine-textured silt loam soil that is punctuated with holes dug by badgers and coyotes, and an artesian spring that is located nearby to serve as a water source for rainfall simulation.

CHARACTERIZATION OF LARGE MAMMAL BURROWS

During March, fieldwork was conducted at the study site to initially characterize the mammal excavations. Information was collected on the size, shape, and configuration of the holes to determine the best approach for evaluating their role as a factor in water entry to deeper soil layers.

Numerous northern pocket gopher (Thomomys talpoides) mounds were found, suggesting that an abundant prey base was available for badgers and coyotes. Many large animal excavations of various ages and depths were found. There appeared to be two distinct kinds of large mammal holes. The majority of the holes were vertically compressed (shaped like an egg lying on its side) and were probably dug by badgers. The second type of hole was horizontally compressed (shaped like an egg standing on end) and appeared to be coyote excavations.

Methods

Large mammal holes were marked with numbered stakes for future identification, and assigned an age class. The top and bottom diameters, length, and vertical depth were estimated (Figure 2). We also recorded whether the hole appeared to have been dug by a badger or a coyote and the orientation of the soil castings relative to the hole opening (up-slope, down-slope, or along the sides of the hole).

Although it was not possible to determine an absolute age of the holes, we assigned a subjective age class to each marked hole. Age class No. 1 was assigned to holes that were recently excavated (1 day to 3 months). The castings for these

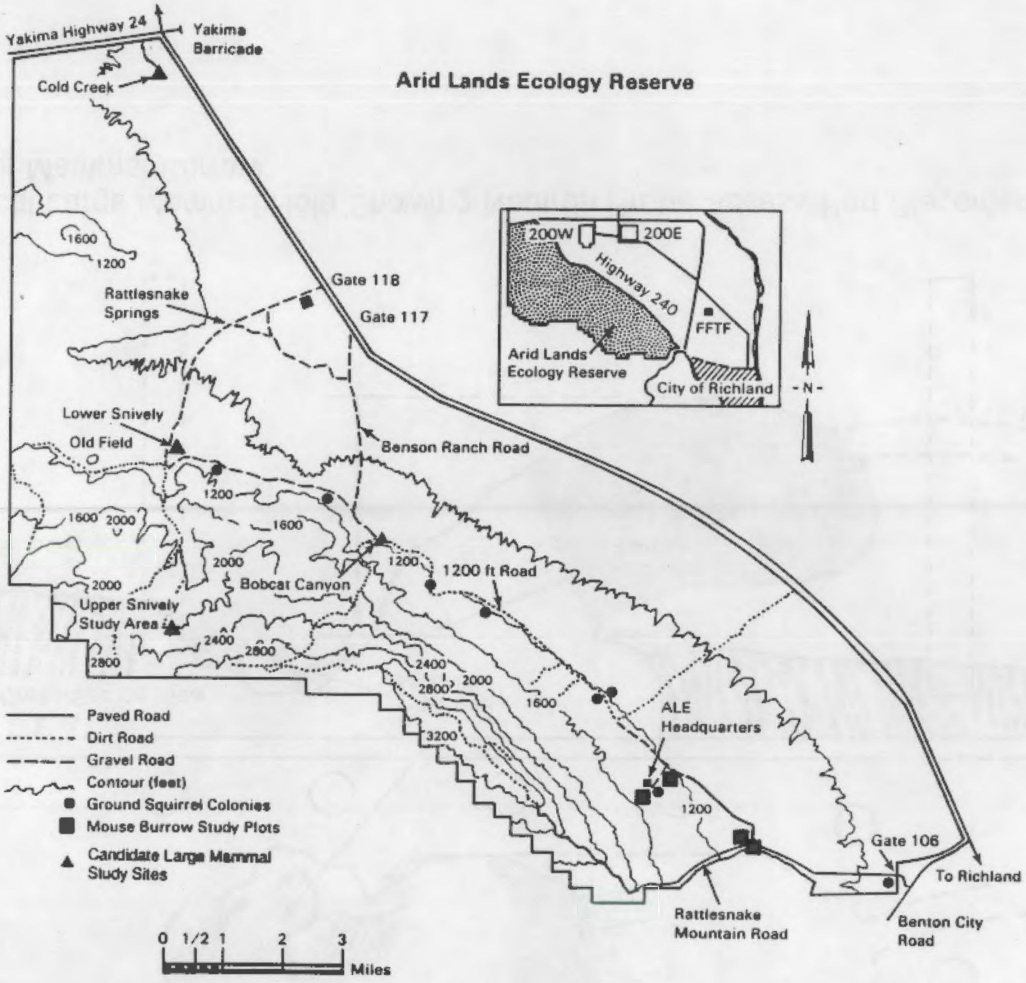

FIGURE 1. Animal Intrusion Field Study Plots on the Arid Lands Ecology Reserve

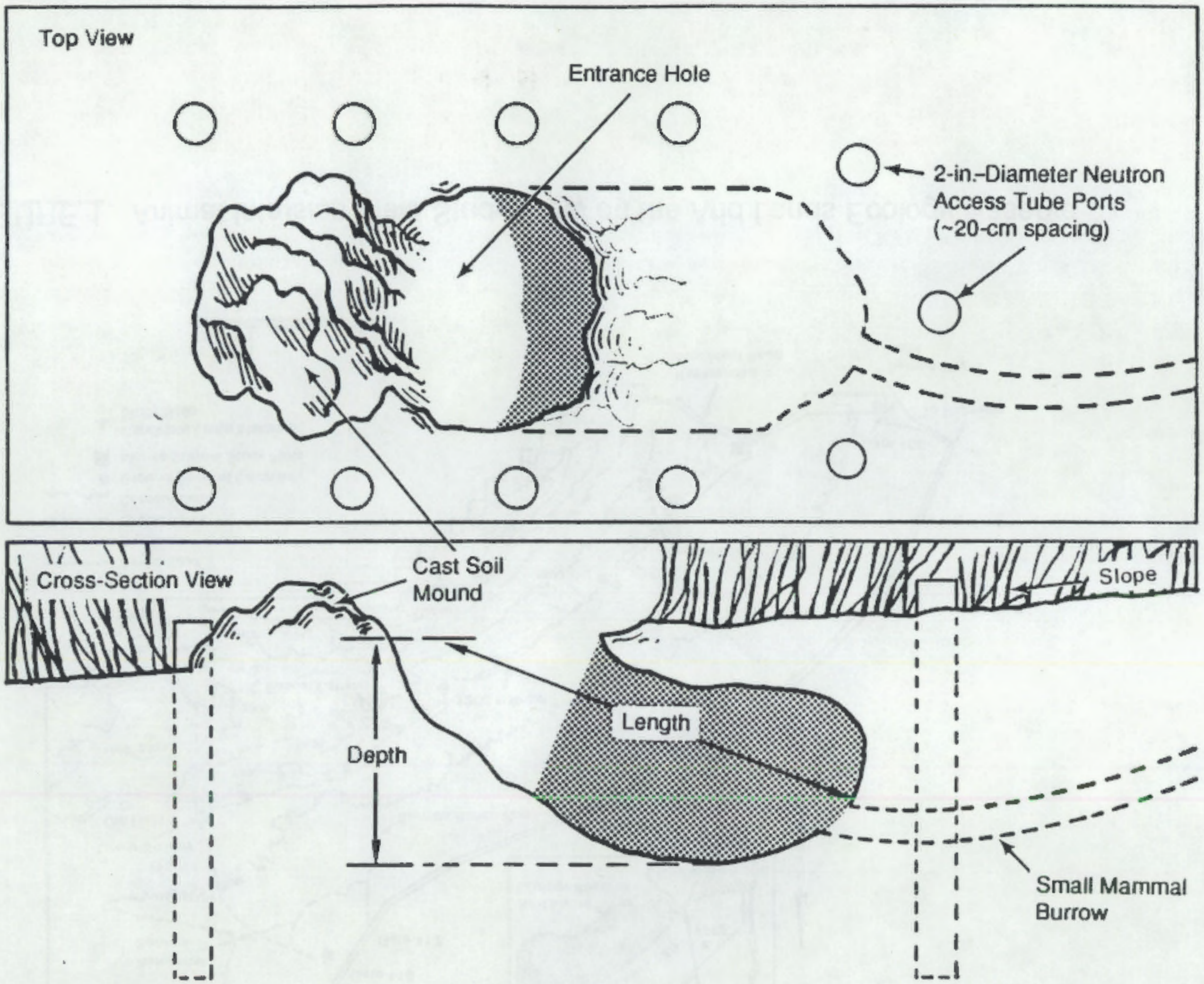

FIGURE 2. Typical Large Mammal Hole Showing Neutron Probe Access Port Placement and Connecting Small Mammal Burrow

holes were not well packed, and no vegetation was growing on them or within the holes. Claw marks were usually evident on the walls of the hole. Age class No. 2 consisted of holes with well-packed castings, and vegetation growth, if present, was limited to newly sprouted seedlings either in the hole or on the castings. No standing dead (previous season's growth) vegetation was present. Thus, age class No. 2 holes were dug sometime after the initiation of the last full growing season, but before the current growing season. Most of the vegetation at the site consists of winter annuals that germinate after the fall rains begin (September through November). Thus, age class No. 2 holes appear to have been excavated sometime between late winter and fall 1987, and we estimate their age at approximately 6 to 15 months. Age class No. 3 holes had abundant vegetation growth, including standing dead vegetation [mostly fall germinating cheatgrass (Bromus tectorum)], either on the castings and/or in the hole. At a minimum, these holes must have been excavated before October 1986. It is difficult to estimate the age of class No. 3 holes, but they were a minimum of about 16 months old, and could be several years old.

A fourth age class of large mammal excavations, which exist as remnants, were not included in the analysis. These excavations appear as irregularities in the soil surface that have been filled and smoothed to the extent that they no longer appear as holes. With the existing vegetative cover at the site, age class No. 4 hole remnants are not readily visible and can be distinguished only by parting the vegetation and closely inspecting the ground surface. However, they contribute to microtopographical relief.

Results and Discussion

Physical characteristics of 73 large mammal holes were obtained at Upper Snively old field (Table 1). Holes appear to have been excavated by both coyotes (17%) and badgers (83%). Approximately two-thirds of the holes were essentially vertical, with the remaining one-third extending diagonally below the soil surface. Diagonal holes were generally more than 50 cm in length. A pattern was apparent for the distribution of the soil cast to the surface during digging. For two-thirds of the holes, the cast soil was deposited immediately down-slope from the opening; for about 20 to 30% of the holes the material was at the same level (along the sides of the hole); and for <10% of the diggings the soil was positioned up-slope (Table 1). Even though the slope was gentle, there was a definite selection for cast soil to be deposited down-slope. It would require less energy to move the castings down-slope, and loose soil would be less likely to fall back into the hole.

TABLE 1. Characteristics of Holes Dug by Large Mammals In Upper Snively Old Field

Age		Mean	Mean	Length	Tailing Location on Slope (%)		
Class	N	Dia. (cm)	Depth (cm)	(cm)	Down	Up	Level
1	9	28.2±3.3(a)	23.6±3.6(a)	52.4±4.8(a) (5)(b)	67	11	22
2	50	29.6±0.9	19.5±1.2	44.1±4.8 (15)	63	10	27
3	14	30.2±1.4	16.9±2.0	46.0±6.0 (3)	67	0	33

(a) ± 1 standard error (SE).
(b) Sample size.
N = Number

Also, several of the large mammal-excavated holes intersected small mammal burrows. Because the diggings occurred while the larger mammals were attempting to capture prey, it is logical that the holes intersect and/or follow small mammal burrows (northern pocket gophers in this case).

PRELIMINARY FIELD STUDIES

Preliminary studies were conducted to test methods for measuring changes in soil moisture beneath large animal holes and to make initial observations on impacts of these holes on the distribution of surface water occurring as precipitation. One objective of the large mammal burrow study was to evaluate changes in soil moisture through time, which requires repeated measurements of soil moisture at a single location. The destructive nature of gravimetric sampling eliminates its use for measuring changes in soil moisture through time. Conductivity probes (Gardner 1986) were tested because they offered an alternative to neutron probes. We felt that conductivity probes would disturb the site less, require less field time in making readings, and perhaps offer some methods for reading from probe to probe that could provide quantitative data on greater soil volume than would be feasible with neutron probes.

Conductivity Probes

We tested a method for soil moisture measurement that appeared to be simple and rapid. It consisted of a conductivity probe (Gardner 1986) fashioned with a number of electrodes evenly spaced along a wooden dowel that was inserted into the soil beneath animal burrows. An alternating current bridge was used to detect changes in electrical resistance of the soil beneath paired electrodes. Changes in resistance were believed to be inversely related to changes in soil moisture. The instrument included a switch to advance the reading over consecutive pairs of electrodes such that a vertical profile of electrical resistance could be read over the length of the probe (through a defined soil profile). A single prototype was designed and constructed by Melvin Campbell (Pacific Northwest Laboratory), and initial results showed some promise. Several probes were then built and tested under realistic field conditions.

Methods

A field site for testing the conductivity probes was selected near a hydrology study site at the entrance to Bobcat Canyon on the Arid Lands Ecology (ALE) Reserve (Figure 1). The area has silt loam soil similar to that of the primary study site in Upper Snively old field. A site was selected that contained four badger holes located within a few meters of one another and that were also located near a temporary pond that could serve as a water source. Sixteen conductivity probes were installed such that four were positioned under the badger excavated holes, four were placed under artificially constructed holes (made to resemble animal excavations), four were under constructed holes having connected simulated small mammal burrows (approximately 2.5-cm-diameter holes going down from the bottom), and four probes were installed as controls located away from any known holes or burrows. The simulated animal holes were dug with hand tools to the same general size and shape of naturally excavated holes. The castings were packed into gently sloping mounds and oriented on the down-slope side of the holes.

Initial conductivity probe readings were obtained before making two 30-min applications of simulated rainfall approximately 24 hr apart. Conductivity probe readings were attempted immediately after the first rainfall application, which totaled approximately 3.0 cm, but the instrument batteries failed, and readings were delayed until the second day. After that set of readings was obtained, a second rainfall application was made (3.3 cm), and conductivity measurements were again taken.

Results and Discussion

Figure 3 shows a representative plot of changes in electrical resistance vs. depth for the pre-rainfall and each of the post-rainfall soil conditions. In theory, increases in soil moisture should increase the electrical conductivity of the soils (decrease the resistance). The pre-rainfall curve is positioned above the curve for the measurement after first rainfall, and that curve is above the curve obtained after a second application of rain (Figure 3). Thus, the nature of the relative response of soil electrical resistance to wetting, that is lower resistance with increased wetting, is as anticipated. Also, all three curves converge at approximately 55 cm, indicating a depth at which no apparent change in soil moisture occurred (i.e., a wetting front).

An apparent anomaly exists with respect to the overall shape of the curves, particularly for the two post-rainfall curves. We would anticipate that the surface soils would be relatively wetter than the deeper soils, especially beyond the depth of maximum water penetration. However, the curves show a lower resistance (suggesting more moisture) in the 60- to 90-cm depths than they do between 5 and 20 cm.

Conductivity vs Gravimetric Analysis

To evaluate this anomaly we took gravimetric soil samples in conjunction with the resistance readings after the second rainfall.

Methods

Soil samples were taken down to a depth of approximately 40 cm. The samples were returned to the laboratory where they were oven dried to permit calculation of soil moisture content by difference between wet and dry weights.

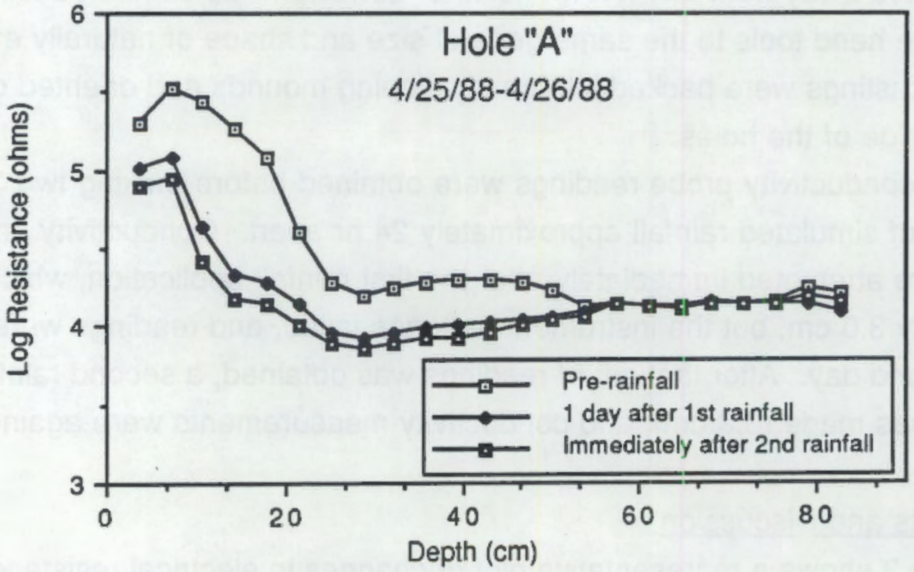

FIGURE 3. Conductivity Probe Resistance Measurements Taken from Beneath a Badger Hole Before and After Simulated Rainfall

Results and Discussion

The conductivity probe readings appear to be erratic in the sense that changes in resistance occurred that cannot be accounted for by observed differences in gravimetric soil moisture (a sample plot is presented in Figure 4). The gravimetric soil moisture readings show approximately 20% soil moisture near the soil surface and drop rapidly across the wetting front to about 6 or 7% at the 25 cm depth (Figure 4). The conductivity probe readings oscillate to the extent that it is difficult, at best, to distinguish the wetting front based on data from this particular probe.

Conductivity vs Neutron Probe Measurements

To further evaluate the usefulness of conductivity probes to detect changes in soil moisture we installed neutron access probe entry ports near several of the control probes.

Methods

The neutron probe ports were installed 15 cm from the control conductivity probes and parallel to them. The site was irrigated with a garden sprinkler, and conductivity and neutron probe measurements (Gardner 1986) were taken.

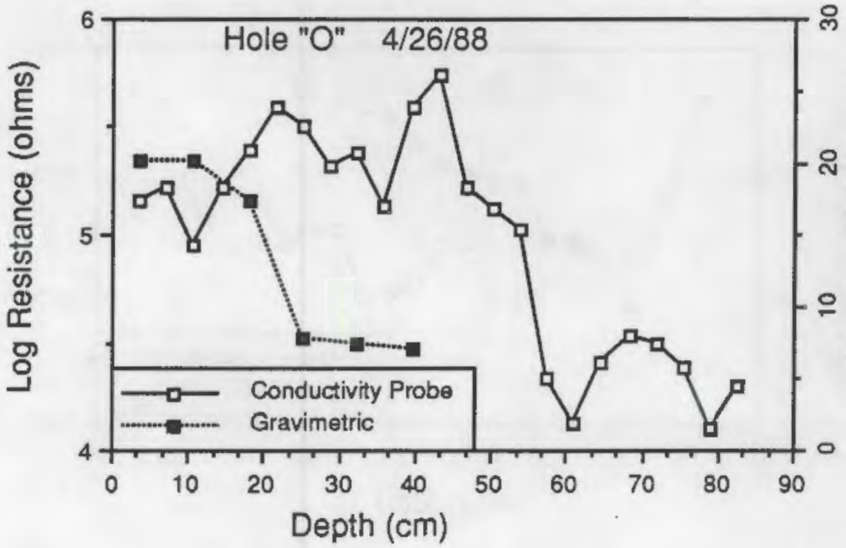

FIGURE 4. Comparison of Gravimetric Percent Soil Moisture Measurements and Conductivity Probe Resistance Readings

Results and Discussion

Figure 5 compares the log (base10) of resistance for the conductivity probe and counts for the neutron probe, each plotted against soil depth. Because resistance decreases with increasing soil moisture, and the reflected neutron count increases, we expected the two methods to mirror one another. Again, we found oscillations in the conductivity probe readings that could not be readily explained.

Based on the inconsistencies from one conductivity probe to another and the oscillations in resistance measurements that have no apparent relationship to soil moisture, we abandoned the conductivity probes in favor of the neutron probes.

Water Accumulation in Large Mammal Burrows

Visual observations were made during two 30-min rainfall applications to determine the extent to which surface water would enter badger holes and artificially constructed holes. Runoff was generated over the application area and could be observed flowing into some of the holes. After several minutes of 6.4 cm/hr simulated rainfall, water began accumulating in the bottoms of several holes. Observations were recorded as to the status of water in the holes after each rainfall application. By the end of the first application, 9 of the 12 holes had filled completely with water. Eleven of 12 holes had filled with water by the end of the second rainfall simulation. A distinction between the two applications involved the antecedent moisture conditions at the time

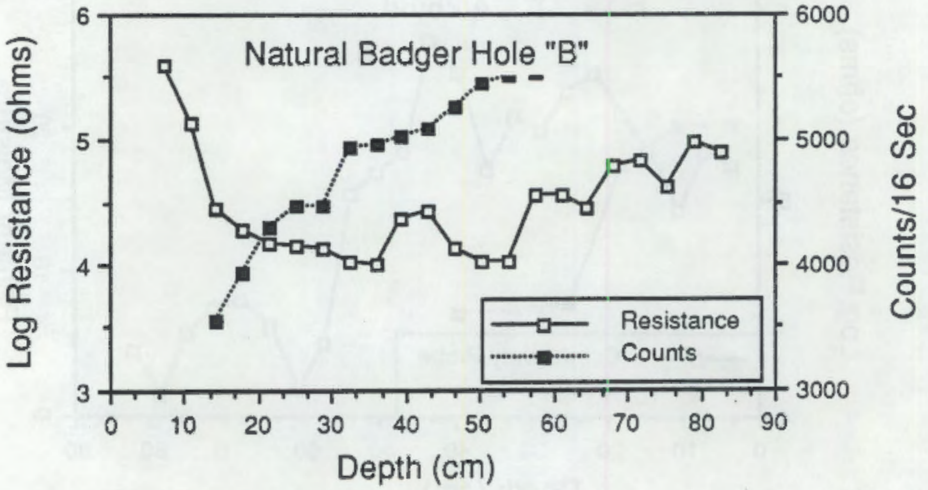

FIGURE 5. Comparison of Conductivity Probe Resistance Readings Vs Neutron Probe Count Data

of application. The surface soil was essentially dry at the beginning of the first application. Two days later, when the second application was made, there was considerable residual moisture in the surface soil. The expected result was that runoff would normally occur earlier, and that the total amount of runoff for the event would be greater in response to decreased infiltration. Thus, an increase in the number of holes filling with water was expected for the second rainfall application.

This preliminary field study yielded several important observations. First, rainfall can collect in holes excavated by large mammals. It appears that water collecting in the holes may be from three sources. The first source is the direct deposition of rainwater that falls within the confines of the surface opening. A second source is water that runs into each hole from the micro-watershed created by the animal during digging. Much of the soil that is cast to the surface next to the hole creates a microtopographical relief that slopes toward the opening. Although no measurements have yet been made for the large mammal-excavated holes, we believe that the contributing area of this micro-watershed may be several times larger than the surface area of the hole. The third source of water entering the hole is from surface runoff that is generated up-slope from holes that are on sloped surfaces. Quantities of this water may be voluminous, and its entry into the holes may be enhanced by the damming effect provided by cast soil deposited on the down-slope side of the holes (Figure 2).

INFILTRATION RESPONSE TO NATURAL RAINFALL

Soil sampling was conducted on June 1, 1988, from a subset of large mammal-excavated holes on the Upper Snively study area to determine the distribution of moisture beneath holes resulting from a natural rainfall event that occurred on May 28, 1988. The rainfall recorded for that date at the Hanford Meteorology Station was 0.71 cm, but no record exists for the Upper Snively study area. Our best approximation for that rainfall amount is 1.47 cm based on the following relationship from Thorp and Hinds (1977):

$$Y = 0.196 + 1.355 X,$$

where X is the recorded precipitation for the meteorological station, and Y is the precipitation amount for Upper Snively.

Methods

Ten large mammal holes having an average depth of 19.7 ± 1.6 cm (1 SD) were sampled with an Oakfield soil corer through the lowest point at the bottom of each hole. Five vertically spaced, 10-cm-long soil increments were obtained from each core. For each hole sampled, equivalent control samples were obtained approximately 3 m away at the same depths relative to the soil surface. Soil samples were returned to the laboratory where they were oven dried to permit calculation of soil moisture content by calculating the difference between wet and dry weights.

Results and Discussion

Average soil moisture values from samples taken through the bottom of mammal holes and from nearby control locations are shown in Figure 6. Soil moisture values taken over the 10-cm increments are plotted at the mid-range point. Because the holes were all about 20 cm deep, the actual depths from the soil surface are approximately 20 cm greater than the values shown in Figure 6. The control locations show an increase in gravimetric soil moisture content from 9 to > 11% with depth. It appears that moisture from the rainfall 3 days before sampling did not penetrate the 20+ cm distance from the soil surface to the first control sample (5 cm below the bottom of the dug holes). However, samples obtained through the bottom of the holes at the first sampling depth had elevated soil moisture concentrations relative to the controls.

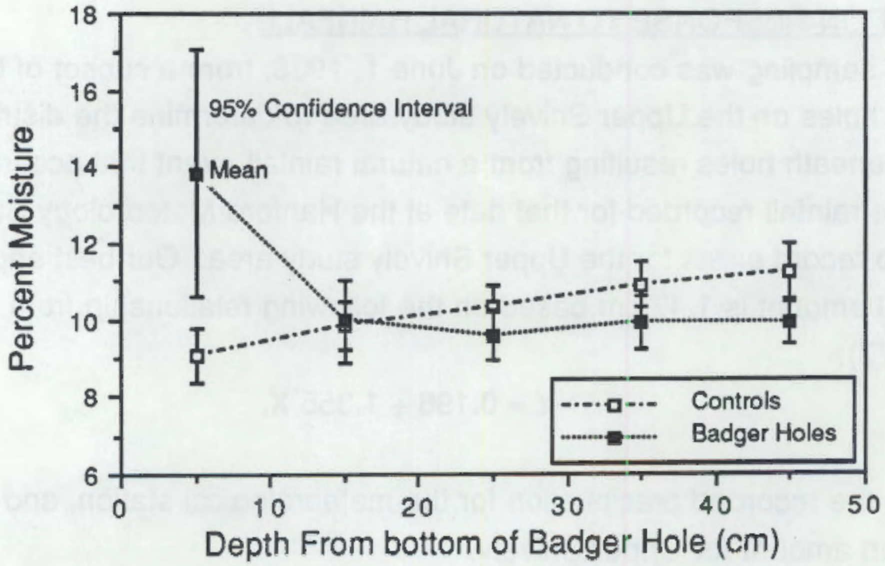

FIGURE 6. Mean Gravimetric Soil Water Below Large Mammal Holes Following Natural Rainfall Event

A significant and unexpected result is observable from samples taken below the wetting front. Soil below the holes, which is beyond the wetting front, appears somewhat drier than control samples obtained at the same depths (Figure 6). (Additional data and discussion on this observation are provided in the following section on simulated rainfall.)

INFILTRATION RESPONSE TO SIMULATED RAINFALL

High-intensity natural rainfall that might produce significant runoff and contribute to deep-penetrating infiltration via animal burrows is relatively infrequent, and therefore cannot be relied on to produce observational data. Therefore, we used simulated rainfall to determine the extent of rainwater penetration below large mammal holes in the Upper Snively study area (Figure 1).

Methods

A rotating-boom rainfall simulator (Renard 1985) was used to apply high-intensity rainfall to large mammal excavations. Holes were selected to represent the various depths that occurred at the study site. Five holes greater than 40 cm and 5 holes less than 40 cm in depth were selected. One constraint to the selection of individual holes was the need to have several of them clustered within a 15.2-m diameter (practical rainfall application limit for the simulator) so that we could apply rainfall to several holes at the same time, thereby minimizing the number of applications required. We located nine holes that could effectively be covered during three rainfall applications. A tenth hole was maintained as a control and was not subject to artificial rainfall.

A set of neutron access port tubes was installed around each large mammal hole. Long tubes (1.4 m in length) were installed around the deeper holes (> 0.4 m), and short tubes (1.1 m in length) were placed around the shallow holes (< 0.4 m). Tube length was selected such that tubes would extend several decimeters below the bottom of the holes. The tubes were installed approximately 20 cm apart such that in plan view they formed a U configuration with the bottom of the U nearest the deepest part of the hole, and the opening of the U on either side of the hole opening (Figure 2). Because many of the deeper holes were dug diagonally downward, the longer holes required a greater number of tubes.

The neutron access port tubes were cut from 52-mm-outside-diameter aluminum pipe (3.3-mm wall thickness) and installed using an auger to bore through the tube. The auger used was slightly smaller in diameter than the tube, and a mallet was used to drive the tube into the hole after removing each 15- to 20-cm increment of soil. This method provided an exceptionally snug fit because the tube wall actually shaved the last few millimeters of soil from the hole wall. The soil surface around each tube was sealed with a narrow ring of latex to prevent water that might accumulate near the tube from running down the side of the tube. Each tube was capped with a polyvinyl chloride cap to prevent water or debris from entering.

A nearby drainage depression was dammed and lined to provide a temporary pond to serve as a water source for the simulations. An existing pipeline from a nearby spring was diverted to the impoundment location to provide water.

An initial conditioning application of rainfall consisting of 6.4 cm/hr for 10 min was applied to each treatment area on July 21, 1988. The purpose of the conditioning rainfall was to provide an initially moist surface soil. At this time of year (July) the surface soil was very dry. The soil was conditioned to maximize the potential for generating runoff and thus provide an opportunity to develop surface runoff that could enter the animal holes. Thirty min after conditioning each site, the treatment application of 6.4 cm/hr for 20 min was applied. This application was chosen to simulate the expected 1000-year return frequency storm (2.5 in/hr for 20 min) as estimated by Stone et al. (1983).

Initial neutron probe readings were made before application of simulated rainfall at 5-cm intervals, beginning 15 cm below the surface. Subsequent readings after rainfall were made at either 5- or 10-cm intervals. The first post-rainfall set of readings was obtained approximately 24 hr after the rainfall, and subsequent readings were taken at increasing time intervals for the next several weeks. Each reading is a 4-sec count normalized to a 16-sec count time.

We used Mann-Whitney U tests (Conover 1971) to compare pre-rainfall neutron probe soil measurements from around and below animal holes with the surrounding control areas. Because our calibration data are incomplete, the comparisons are made using neutron count data, which reflect soil moisture content. This testing was prompted by the results from the gravimetric analyses, suggesting that soils directly below animal holes were actually drier (beyond the zone of immediate recent wetting) than nearby control soils at equivalent depths (see section on infiltration from natural rainfall). We compared animal holes and control locations at 15, 45, and 95 cm depths. There were a total of 78 neutron probe readings made at the 15 and 45 cm depths and 75 observations at the 95 cm depth. There were 25 control probe readings at each depth.

Results and Discussion

Pre-rainfall soil moisture content, based on neutron probe readings, was significantly lower in the vicinity of animal holes than away from the holes at the 15-($Z = -5.027$, $P < 0.001$); 45-($Z = -3.481$, $P = 0.001$); and 95-($Z = -3.039$, $P = 0.002$) cm depths. The neutron probe results not only support the gravimetric sampling results, indicating drier soil below the holes, but also show that the dry zone surrounds the animal burrows.

As we attempted to reconcile these results, we recalled some observations made in the field during sampling. The vegetation at the study site is dominated by cheatgrass (Bromus tectorum). Although we have not yet made vegetative cover measurements at the study site, it is clear that cheatgrass is punctuated with irregular spacings of forbs. At the time of the June 1, 1988 soil sampling (see section on infiltration response to natural rainfall), the presence and distribution of the forbs was most apparent because the cheatgrass had completely finished its annual growth cycle and was dry and brown. However, the forbs were still green and actively growing. It was apparent that the distribution of the forbs coincided with the occurrence of the disturbed soils at animal burrows. Closer inspection revealed that typically several forbs (primarily Sisymbrium altissimum) were growing around each hole. For some holes, forbs had actually sprouted inside and were rooted in soil several centimeters below the surrounding soil surface. This observation provides a possible explanation for the dry, deep soil conditions below large animal-excavated holes. Moisture that had penetrated the soil below the rooting depth of cheatgrass may have been extracted by the deeper rooting forbs. Thus, digging done by large mammals resulted in annual forb growth around the holes. Those plants may have extracted deep soil water during the late winter and early spring growing seasons. Both of these plant species are widely distributed on the Hanford Site and will probably be present in any plant community that ultimately occupies the surface of protective barriers. It is also possible that the increased exposed surface area because of badger holes may have contributed to increased evaporation in the holes and thus drier conditions below the soil surface in comparison to nearby undisturbed sites.

Figure 7 presents a representative data set for animal hole No. 82 showing neutron probe count data obtained before application of artificial rainfall and up to 3 weeks post-rainfall. The pre-rainfall and post-rainfall curves converge at approximately 75 cm, indicating the depth of water penetration. The wetted soils appear to have dried over the 3-week interval from rainfall to the last measurement, as the curves representing the later dates shift down (drier) through time (Figure 7). During this time, the dominant cheatgrass cover was inactive, but forbs growing near the holes were still active. Figure 8 shows a similar plot of neutron count data for a nearby central location vs depth for pre-rainfall and the first (24-hr) post-rainfall measurement.

The average maximum depth of water penetration for each of the nine animal holes was 55.6 ± 4.7 (1 SE) cm. For seven control sets, the average maximum depth of water penetration was 32.1 ± 1.8 cm (1 SE) (36.3 cm if an eighth control set that showed abnormally deep moisture penetration is included). The additional control neutron probe port that showed deep water penetration was excavated to determine whether there were any physical characteristics of the site that might explain the abnormally deep water penetration. We found several small, nearly vertical holes, possibly made by small mammals, that may explain the deep water penetration for this control probe.

Based on the neutron probe count data, we determined that sufficient water entered the animal holes to increase the depth of water penetration for seven of the nine holes that received high-intensity simulated rainfall.

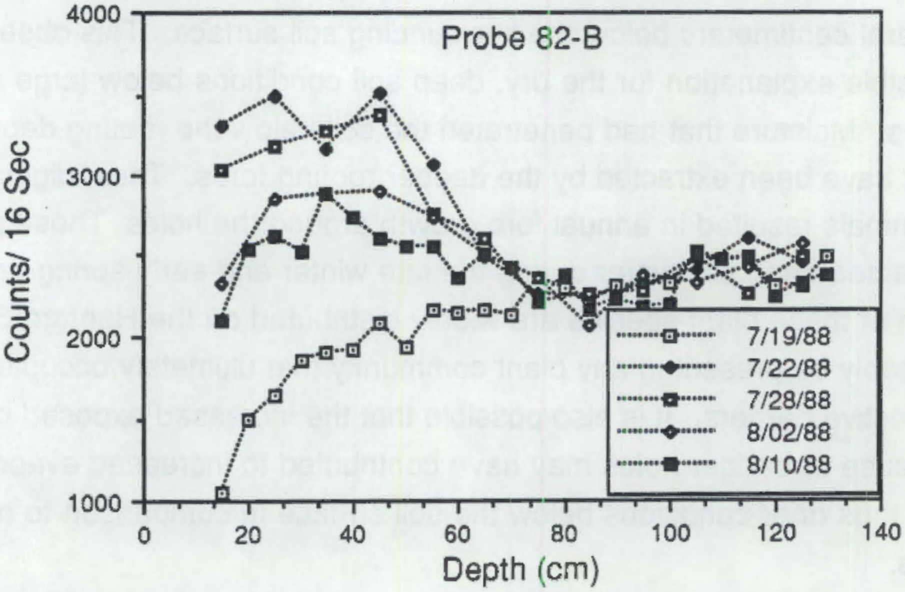

FIGURE 7. Neutron Probe Counts Through Soil Profile Around Large Animal Holes Before and After July 21, 1988 Simulated Rainfall

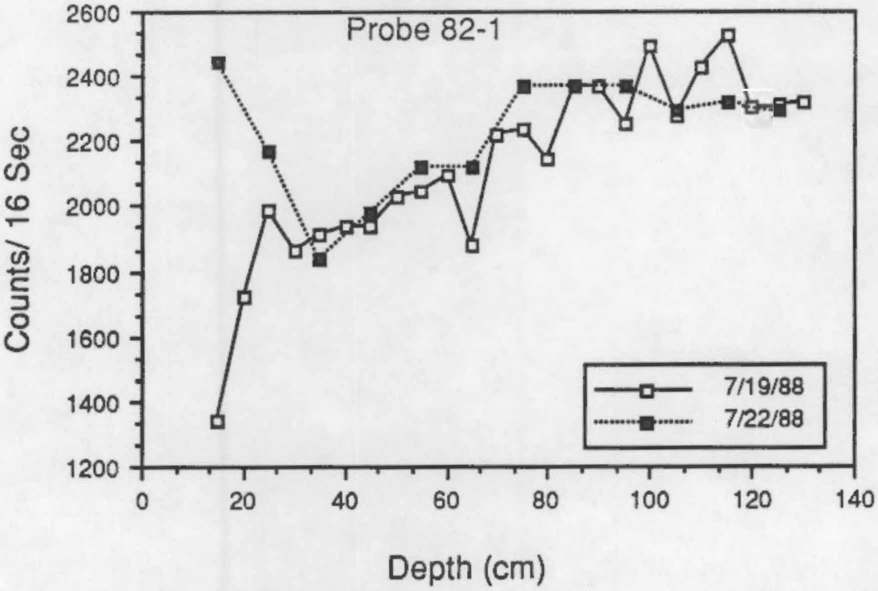

FIGURE 8. Neutron Probe Counts Through Soil Profile for Control Location Away from Large Mammal Holes

ANIMAL BURROW CHARACTERISTICS (TASK B)

The objective of this task was to obtain quantitative estimates of animal burrow parameters for species of burrowing animals (vertebrates and invertebrates) likely to inhabit the waste sites over the next 10,000 years (Landeen et al. 1987). Information on animal burrow characteristics (e.g., depth of burrow, volume of burrow, life of burrow, etc.) is necessary for input into the modeling task (Task D) to address issues of major concern (water infiltration, erosion of the soil cap, and waste transport) relative to animal burrowing on protective barriers (Table 2).

The first phase of this task was an extensive review of available literature on animal burrow characteristics. This review was used to identify those species and burrowing characteristics for which little or no published information existed. Within the constraints of budget and time, fieldwork was then initiated on these identified topics.

Species selected for study included the badger, marmot (Marmota flaviventris), prairie dog (Cynomys spp.), Townsend's ground squirrel (Spermophilus townsendii), northern pocket gopher (Thomomys talpoides), Great Basin pocket mouse (Perognathus parvus), kangaroo rat (Dipodomys spectabilis), and western harvester ant (Pogonomyrmex owyheei). Species were selected for study if they were already present in the general area and were important burrowing species (marmot, badger,

TABLE 2. Relationship Between Animal Burrowing Characteristics and Major Technical Concerns(a)

	Technical Concerns		
Animal Burrow Characteristics	Soil Erosion	Water Infiltration	Waste Transport
Depth		IN(b)	IN
Volume		IN	IN
Amount of soil displaced	IN	IN	
Number of burrows/ individuals	IN		IN
Life of burrow		IN	

(a) From Table 4.0, Landeen et al. (1987:21).
(b) Input needed to resolve technical concerns.

ground squirrel, pocket gopher, pocket mouse, and western harvester ant), or if they were important burrowing species present in similar western habitats (kangaroo rat and prairie dog). The selection of these species is preliminary; final selection depends on the chosen climate scenario, which has yet to be decided.

LITERATURE REVIEW (SUBTASKS 1-5)

Methods

Published literature was examined for the following animal burrow characteristics: depth, length, diameter, total volume, volume by depth, life, number per individual animal, number per area, amount of soil displaced to the surface, and density of burrowing animals. Information recorded during the literature search included whether data on these specific burrowing characteristics were available and, if so, the relative quality of the data. Because of the limited amount of published information available on some species, data were also recorded for closely related species.

Results and Discussion

The results from the literature review are summarized by reference for each species (Appendix A) and combined into an overall summary table (Table 3). Little or no information is available on most burrowing characteristics for the badger, marmot, and harvester ant (Table 3). In addition, little information is available for any species reviewed on the expected lifetime and fate of burrows once constructed. Other aspects of animal burrowing that are poorly understood for any of these species are the number of burrows constructed per individual animal and the amount of soil displaced to the surface during burrow construction.

Based on the literature review, the burrowing characteristics of the badger, marmot, and harvester ant require additional fieldwork for input into the modeling effort (Task D). It is likely that some additional information will be obtained on badger burrows during Subtask 2 of Task B (water infiltration in response to large burrowing mammals) of this study. Obtaining additional information on marmot burrows will be difficult because of their low densities, and because they generally dig their burrows in rocky hillsides where excavation is difficult. Harvester ants are relatively common on the Hanford Site and appear to be a good candidate for additional field studies. Field investigations were begun in FY 1988 on the life and fate

TABLE 3. Relative Quality of Information Available on the Burrow Characteristics of Selected Species of Burrowing Animals

	Burrow Characteristics									
Species	Depth	Length	Dia.	Total Vol.	Vol. by Depth	Life	No./ Indiv.	No./ Area	Amount of Soil Displaced	Animal Density
Pocket mouse	Good	Fair(a)	Fair(a)	Fair(a)	Fair(a)	None	None	None	Poor	Good
Kangaroo rat	Good	Good	Good	Good	Good	None	Fair	Good	Good	Good
Pocket gopher	Good	Good	Good	Fair	Poor	None	Poor	Fair	Good	Good
Ground squirrel	Good	Good	Good	Good	Good	Poor	Poor	Fair	Fair	Good
Prairie dog	Good	Good	Good	Fair	Fair	Poor	Fair	Good	Poor	Good
Badger	Poor	Poor	Poor	None	None	None	Fair	Good	None	Good
Marmot	Poor	Poor	None	None	None	Poor	Fair	Good	None	Fair
Harvester ant	None	None	None	None	None	Good	None	Good	None	Good

(a) D. Landeen, Westinghouse Hanford Company, personal communication.

of animal burrows because 1) little or no information exists on this aspect (Table 3), 2) field studies on this topic will require an extended study period, and 3) the information is needed for input to the modeling effort.

LIFETIME AND FATE OF ANIMAL BURROWS (SUBTASK 5)

The BIOPORT model (McKenzie et al. 1986) will be modified to evaluate the impact of animal burrowing on water infiltration, erosion, and waste transport. Currently, this model converts animal density/year into the number of burrows present/area/year. It is assumed in this model that individual animals construct a new burrow each year, and that all old burrows collapse each year. Undoubtedly, these assumptions are not realistic, particularly for the larger burrowing animals. However, little published information exists on the lifetime and fate of animal burrows (Table 3) to improve on these assumptions.

The objectives of this subtask are to determine 1) how long a burrow exists, and 2) whether abandoned burrows are reused by other individuals or species, thereby extending the life of these burrows. In conducting this subtask, we assumed that animal burrows increase water infiltration, which is the current topic of investigation in Task A. If this assumption is incorrect, then it is not necessary to evaluate the lifetime and fate of animal burrows for the protective barriers program. However, we felt it was necessary to begin fieldwork on this subtask as soon as possible because 1) some previous studies (Reynolds 1958; Grant, French, and Folse 1980) suggest that animal burrows increase water infiltration, and 2) fieldwork on animal intrusion is proposed to extend only over a 3-year period, and this subtask will require marking and monitoring individual burrows over several years.

Fieldwork was restricted to the smaller relatively common burrowing animals [Great Basin pocket mice, Townsend's ground squirrels, and deer mice (Peromyscus maniculatus)] because the burrows of larger animals (badgers and marmots) are likely to persist for extensive periods of time, and are, thus, beyond the scope of this study. For example, the average life of an arctic fox (Alopex lagopus) den has been roughly estimated to be 330 years (Macpherson 1969).

Methods

Fieldwork was conducted on the Arid Lands Ecology (ALE) Reserve between April and August 1988. The ALE Reserve was selected as the study site because its protected nature offers a fair degree of assurance that any burrows marked during this study will be undisturbed over an extended period of time. Efforts were made to restrict individual study sites on the ALE Reserve to soil types similar to those planned for the barrier.

Townsend's ground squirrels are colonial and are only active above ground between late winter and early summer (Davis 1939). Colonies of ground squirrels were located by walking extensive areas of the ALE Reserve between April and mid-June. Once a squirrel colony was located, the identity of the squirrel burrow was confirmed by presence of the squirrel, its tracks, or feces. Burrow entrances with recent squirrel activity were marked with a 1.8-m steel fence post and numbered metal tag. Burrow entrances were subjectively classified into three categories: major burrow (large mound of excavated soil and multiple burrow entrances), simple escape burrow (no soil mound and only one apparent burrow entrance), or intermediate-size burrow (small soil mound and only a couple of burrow entrances). Burrows were revisited periodically to determine whether they were still being used and their current physical condition.

Areas supporting comparatively high densities of pocket mice and deer mice were selected on the ALE Reserve by examining old trapping records and conducting some preliminary live trapping. Once a site was selected for study, live traps, baited with bird seed and rolled oats mixed with peanut butter, were randomly placed throughout the area. All captured mice were identified to species and sex, weighed, individually marked by toe clipping, and released where captured. Upon their release, attempts were made to follow the mice to the burrow entrances in which they escaped. These entrances were then temporally marked. At least 1 day later, live traps were set at these burrow entrances, and a 5-mm-mesh wire cone was placed over both the trap and cone to limit captures to individuals actually using the burrow. Because this process was time consuming, trapping was not conducted at all burrow entrances in which mice escaped. Burrow entrances, both those confirmed as being active with the wire cones and those suspected as being active (i.e., those in which a mouse escaped, but was not later trapped), were marked with 40-cm-high wire stakes and numbered metal tags. To simplify the relocation of marked burrows, all marked burrow entrances were referenced to either a grid or a line of 1.8-m steel fence posts. Burrows were revisited periodically to determine their current physical condition and whether they were still being used.

Only burrow entrances could be identified and marked in this study. For mice, these marked entrances probably represented discreet burrow systems. However, for ground squirrels, more than one entrance for a given burrow system may have been marked.

Results and Discussion

One-hundred and sixty-nine active ground squirrel burrow entrances were marked in eight colonies (Figure 1, Table 4). Based on excavation patterns, northern pocket gophers and ground squirrels appeared to use some burrows interchangeably; this caused some difficulty in burrow identification, particularly in the 0.5 mile east

TABLE 4. Summary of the Number and Fate of Townsend's Ground Squirrel Burrow Entrances Marked Per Colony on the Arid Lands Ecology Reserve in 1988

	No. of Burrow Entrances		
Colony Name	Marked	Partially or Totally Filled In [(a)]	Excavated by Badgers
Waterplot	24	0 (0.0)	0 (0.0)
0.5 mile west	21	4 (19.0)	8 (38.1)
0.5 mile east	23	11 (47.8)	2 (8.7)
Gate 106	40	17 (42.5)	0 (0.0)
2.9 mile	16	4 (25.0)	0 (0.0)
Headquarters	16	3 (18.8)	2 (12.5)
Lower Snively	6	1 (16.7)	0 (0.0)
Point	23	0 (0.0)	1 (4.3)
Total	169	40 (23.7)	13 (7.7)

(a) Percent shown in ( ).

colony (Table 4). Only those burrows definitely being used by ground squirrels when first visited were marked.

Forty (23.7%) of the marked ground squirrel burrow entrances were partially or totally filled in by early August 1988 (Table 4). The northern pocket gopher appeared to fill in many of these burrow entrances. Whether the deteriorating condition of these burrows was related to the fact that the squirrels were inactive because they were estivating during part of the study (mid-June to August 1988), or because the burrows were abandoned is unknown.

Individual ground squirrels probably used several burrows simultaneously. Many of the burrows classified as simple escape burrows appeared to be comparatively limited in extent underground and were probably used only as temporary refuge from predators while the squirrel was foraging. Those burrow entrances classified as major were probably entrances to burrows in which ground squirrels were resident much of the time. Badgers, presumably in pursuit of ground squirrels, provided evidence suggesting that the major burrows were occupied. More than 30% of the burrow entrances classified as major were excavated by badgers during the short time of this study, and nearly all badger digging at ground squirrel burrow entrances was limited to major burrow entrances (Table 5).

Species other than the badger and northern pocket gopher that were observed using marked ground squirrel burrows during mid-summer included the northern grasshopper mouse (Onychomys leucogaster), Nuttal's cottontail rabbit (Sylvilagus nuttallii), burrowing owl (Athene cunicularia), and several species of invertebrates.

TABLE 5. Number and Fate of Ground Squirrel Burrows on the Arid Lands Ecology Reserve in 1988 by Burrow Type

	Burrow Type		
	Simple	Intermediate	Major
Total no. marked	58	76	35
No. excavated by badger	0 (0.0)[a]	2 (2.6)	11 (31.4)
No. partially or totally filled in	17 (29.3)	9 (11.8)	6 (17.1)

(a) Percent.

Two-hundred and thirteen mouse burrow entrances were located and marked; 19 of these were deer mice burrows, the remainder were pocket mice burrows (Table 6). Most mouse burrows (77.5%) were identified by observing a mouse enter a burrow following release from a live trap. Some of these mice probably entered burrows that they normally did not use in an attempt to escape. However, pocket mice were generally calm following release and would often explore several burrow entrances before actually selecting one. Such behavior suggests that the burrow they finally entered was one that they were at least familiar with.

TABLE 6. Summary of Active Mouse Burrows Marked on the Arid Lands Ecology Reserve in 1988

	No. Pocket Mouse Burrows			No. Deer Mouse Burrows		
Plot	Confirmed[(a)]	Suspected[(b)]	Total	Confirmed[(a)]	Suspected[(b)]	Total
ALE corner	3	31	34	0	0	0
Mountain corner	0	21	21	0	0	0
Mountain grid	5	66	71	0	0	0
Rattlesnake Springs	6	21	66	0	0	0
ALE headquarters	15	26	41	19	0	19
Total	29	165	194	19	0	19

(a) Mouse trapped under wire cone.
(b) Mouse observed entering burrow.

PREDICTION AND INTEGRATION (BIOPORT MODEL) (TASK D)

The objective of the animal intrusion modeling task for the Hanford protective barriers program is to predict cumulative burrow volumes, soil displacement, and radioactive material transport resulting from animal burrowing activity. An existing code, called BIOPORT (McKenzie et al. 1986), which contains an animal intrusion subroutine, was selected as the starting point for the modeling effort. The task this fiscal year was to install and test the model, review the parameters applicable to the protective barriers program, and interact with other tasks to ensure the model input requirements correspond to output from field experiments.

The BIOPORT program was originally developed to calculate waste package degradation and the biological transport of radionuclides from a commercial low-level waste disposal site. Biological components are plant roots and animals. Plant roots absorb radionuclides and translocate them to other plant organs (i.e., roots, stems, and leaves) and subsequently recycle them back to the soil. Animals move soil and accompanying radionuclides from various soil strata to the surface. The computer program calculates concentrations of radionuclides available to the soil column based on waste form/package decomposition. Biological transport of radionuclides is calculated for each year of a specified time period and for each radionuclide in the waste inventory. The code assumes there are three soil layers above the waste site.

For the barriers program, we are interested primarily in the animal portion of the code. In the original BIOPORT code, animal burrowing moved soil and the accompanying radioactive material from each layer to the surface. The surface material was subjected to erosion, and the remaining material was then incorporated into the top soil layer. To remove voids resulting from burrowing, enough soil to fill the void in a particular layer was removed from the next higher layer (going from top to bottom) and evenly mixed with the remaining soil. This resulted in a steady decrease in the volume of the top layer, depending on the rate of erosion. There was no provision in the original code for succession of animal species with time, or a change in burrowing activity beyond the first 2 years.

Parameters for the animal portion of the BIOPORT code are:

1. species or other identifying name
2. total amount of soil excavated by burrowing/year (m^3/ha)
3. range of movement (m) (i.e., depth of burrow)
4. activity in subsequent years compared with first (proportion, <1)
5. proportion of soil moved from each layer (sum = 1).

A sensitivity analysis using the individual parameter perturbation method was conducted on the original code (McKenzie et al. 1986). This method assumes minimal interaction between model input parameters, which is appropriate for the BIOPORT code. For the sensitivity analysis, values of one set of parameters were varied, while all other parameters were held constant. The sensitivity analysis determined that the most important parameter in terms of its effect on the amount of radioactive material brought to the surface was the range of animal movement. Thus, if an animal does not penetrate the waste, no radioactive material is moved.

In evaluating the model for the present needs of the protective barriers program, it appears that the code needs to be expanded to more thoroughly model animal burrowing dynamics, particularly calculation of burrowing depth, burrow volume, and quantity of soil moved to the surface. Work on the animal burrowing parameters subtask has identified several areas of importance, including life of the burrow; burrow reuse by the same or other species; number of burrows per individual, or for social species, the number of individuals per burrow; and succession of animal species. Also, code output needs to be expanded to include burrow volumes as well as radionuclide concentration. This will provide an indication of disturbance for each layer.

Other parameters of interest include making the soil layers unequal volume, and adding an intrusion coefficient for each layer/species, based on the probability of a particular species burrowing into that layer. This will be useful when layers of different material are present over the waste site.

Work has started on expanding the code. Additions so far include having 1) a variable colonization rate (assumes that the species does not appear at the site at peak density in a single year; i.e., it gradually increases in numbers until reaching a stable population level); 2) a reuse index (assumes a species does or does not reuse a burrow); 3) a burrow collapse rate based on burrow age; this is a stochastic feature that is checked yearly; and 4) succession of animal species over time.

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APPENDIX A

LITERATURE SUMMARY ON ANIMAL BURROWING CHARACTERISTICS

TABLE A.1. Summary of Information Available on the Burrowing Characteristics of Selected Animal Species. Data presented as the number of burrows examined or as a eualitative estimate of the amount and value of the information available.

Source of Information	Location of Study	Depth	Length	Diameter	Total Volume	Vol. by Depth	Life	No. per Individual	No. per Area	Amount of Soil Displaced	Animal Density
BADGER											
Lindzey (1976)	UT, ID	Poor	Poor	Poor							
Lindzey (1978)	UT, ID							Fair	Good		
Messick & Hornocker (1981)	ID										Good
Sargeant & Warner (1972)	MN							Fair			
MARMOT AND WOODCHUCK											
Armitage(1962)	WY						Poor	Fair	Fair		Good
Armitage(1974)	CO										Fair
de Vos and Gillespie (1960)	ONT								Good		Fair
Henderson and Gilbert (1978)	ONT								Good		
Merriam(1971)	NY						Poor	Good	Good		
Pattie (1967)	MT, WY	Poor									
Svendsen (1974)	CO								Good		Good
Svendsen (1976)	CO	5	5						Fair		
PRAIRIE DOG											
Archer, Garrett, & Detling(1987)	SD								Good		Fair
Carlson & White (1987)	SD						Poor				
Clark (1971)	WY	2	2	2					Good		
Clark (1977)	WY	2	2	2				Good	Good		Good
Fitzgerald and Lechleitner (1974)	CO							Fair	Good		Good
Garrett, Hoogland, &Franklin(1982)	SD										Fair
Merriam (1902)	Plains	1	1							Poor	Poor
Sheets, Linder, & Dahlgren (1971)	SD	18	18	Fair							
Smith (1958)	KA	Poor							Fair		Fair
Stromberg (1978)	WY								Good		
Tileston and Lechleitner (1966)	CO								Good		Good
Whitehead (1927)	TX	Poor									
Wilcomb (1954)	OK	13	13	13	13	13	Poor				

TABLE A.1. (contd)

Source of Information	Location of Study	Depth	Length	Diameter	Total Volume	Vol. by Depth	Life	No. per Individual	No. per Area	Amount of Soil Displaced	Animal Density
GROUND SQUIRRELS											
Abaturov (1972)	USSR									Fair	
Alcom (1940)	NV	14	14	14							
Arthur & Markham (1983)	ID									Good	Fair
Bartholomew & Hudson (1961)	CA	Poor	Poor								
Broadbrooks (1958)	WA	14	14	14							
Criddle (1939)	MAN	Poor	Poor								
Davis (1939)	ID			Poor							
Desha (1966)	OK	64	64					Fair	Good		
Fitch (1948)	CA						Poor	Poor	Fair		Good
Michener (1979)	ALB										Fair
Reynolds & Laundre (1988)	ID	30			30	30					
Reynolds & Wakkinen (1987)	ID	20	20		20						
Rongstad (1965)	WI	6	6								
Shaw (1925)	WA										Poor
Shaw (1926)	WA	3	2	1		2					
Smith & Johnson (1985)	ID										Good
POCKET GOPHER											
Andersen & MacMahon (1981)	UT										Good
Axthelm & Lee (1976)	NE	Poor									
Best (1973)	NM	98		98							
Buechner (1942)	TX									Fair	
Davis, Ramsey, & Arendale (1938)	TX	Poor		40							Good
Downhower & Hall (1966)	KA	3	3	3							
Ellison (1946)	UT									Good	Fair
Ellison & Aldous (1952)	UT										Poor
Grant, French, & Folse (1980)	CO								Poor	Fair	
Grinnell (1923)	CA	Poor								Fair	
Hakonson, Marteniz, &White (1982)	NM									Good	
Hansen & Reid (1973)	CO	Poor		Poor							
Hickman (1977)	TX	5	5	5	5						
Hickman & Brown (1973a,b)	FL							Good			
Ingles (1952)	CA									Fair	Good
Kalisz & Stone (1984)	FL								Poor	Good	
Mielke (1977)	Summary									Summary	

TABLE A.1. (contd)

Source of Information	Location of Study	Depth	Length	Diameter	Total Volume	Vol. by Depth	Life	No. per Individual	No. per Area	Amount of Soil Displaced	Animal Density
Miller (1957)	CA	9	9	9	9	9			Good	Good	Fair
Reichman & Baker (1972)	TX	76		76							
Reid (1973)	CO										Fair
Richens (1966)	UT		1							Poor	
Shelford (1929)		Poor								Poor	
Vleck (1979)[c]	CA		1	1							
Winsor & Whicker (1980)	CO	Fair								Good	
KANGAROO RAT											
Anderson & Allred (1964)	NV	30	30								
Arthur & Markham (1983)	ID								Good	Good	
Best, Intress, & Shull (1988)	Mexico			Good						Fair	
Bienek & Grundmann (1971)	CA, UT	5	5								
Culbertson (1946)	CA	1		Poor	Poor						
Grinnell (1932)	CA	3	3	20							Poor
Hawbecker (1940)	CA	Poor	Poor								
Holdenried (1957)	NM								Fair		Good
Kenagy (1973)	CA	Poor		Fair			Poor	Good			
Monson & Kessler (1940)	AZ, NM							Fair	Good		Fair
Reynolds (1958)	AZ		Fair	Fair	Fair				Good	Good	Good
Reynolds & Laundre (1988)	ID	23			23	23					
Reynolds & Wakkinen (1987)	ID	19	19		19						
Rosenzweig & Winakur (1969)	AZ										Good
Schroder & Rosenzweig (1975)	NM									Fair	
Tappe (1941)	CA	Poor	Poor	31				Fair			
Vorhies & Taylor (1922)	AZ	Poor	Poor	Poor	Poor				Good		
POCKET MOUSE											
Arthur & Markham (1983)	ID									Good	Good
Criddle (1915)	MB	1	1								
Hoover, Whitford, & Flavill (1977)	NM										Fair
Kritzman (1970)	WA	Poor	Poor								
Kritzman (1974)	WA										Fair
Landeen & Mitchell (1982)	WA	[41collected not publ.]									
O'Farrell et al. (1975)	WA										Good
Reynolds & Haskell (1949)	AZ										Fair

TABLE A.1. (contd)

Source of Information	Location of Study	Depth	Length	Diameter	Total Volume	Vol. by Depth	Life	No. per Individual	No. per Area	Amount of Soil Displaced	Animal Density
Scheffer (1938)	WA, OR	5								Poor	
Schreiber (1978)	WA	5									Good
ANTS											
Baxter and Hole (1967)	WI	2		2	2	2			Good		
Chew (1987)	AZ						Good				Good
Porter and Jorgensen (1988)	ID						Good				Good
Sharp and Barr (1960)	ID								Good		
Sneva (1979)	OR										Good
Willard and Crowell (1965)	OR										Good

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