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CLASSIFICATION AND HYDROLOGICAL CHARACTERISTICS OF SCREE SLOPE DEPOSITS IN THE NORTHERN CRAIGIEBURN RANGE, NEW ZEALAND

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ABSTRACT

Slope deposits occurring beneath the surface layer of loose angular gravel on north Craigieburn Range scree slopes can be subdivided into three significantly different types: nonstratified openwork gravels, primarily associated with scree cones (Type 1); stratified gravels, sands, and silts, generally found beneath the surface of scree sheets and scree gullies (Type 2); and truncated silt-loam subsoils, chiefly associated with patchy scree sheets and stone pavements (Type 3). The kind of slope deposits present can be predicted reasonably well from scree slope form, coupled with surface texture—parameters that are discernible on air photos.

The wide range in physical characteristics of the slope deposits is mirrored by an equally wide range in hydrological characteristics. In the span from coarse Type 1 gravels to Type 3 silts, saturated hydraulic conductivities vary from over 10,000 cm/h to about 10, available water capacities range from nil to over 11 percent, and free drainage to 50 percent saturation may take anywhere from two seconds to two days. Summer field moisture in all but the coarsest subsurface deposits was ample for sustaining plant growth, apparently because of an evaporation barrier created by the coarse surficial scree gravel.

Hydrological response from scree-mantled alpine watersheds will depend on, among other things, the type of deposits present. Type 1 and 2 deposits (scree cones and most sheets and gullies) should respond with very high runoff ratios, with broad baseflow-dominated hydrographs, and with relatively low peak flows. Conversely, Type 3 deposits (stone pavements and some scree sheets) should respond with "flashy" stormflow-dominated hydrographs, higher peak flows, and somewhat lower runoff ratios.

INTRODUCTION

Scree slopes, a nearly ubiquitous alpine landform in New Zealand, are slopes that are mantled by a layer of relatively coarse, unconsolidated rock debris and are largely unvegetated. The term *scree* is generally synonymous with *talus* and refers specifically to the surface gravel layer on a slope, although talus is often restricted to the more specific context of accumulated rock debris at the base of a cliff (American Geological Institute, 1962). The term *scree slope deposit* will be used here to include the surface gravel layer plus any unconsolidated slope deposits that may lie beneath.

Very little of the published literature on screes and scree slopes considers the deposits below the surface. Studies focus either on the form and characteristics of the landform surface and relate these to observed or inferred geomorphic processes (e.g. Caine, 1963, 1967; Gardner, 1971; Howarth and Bones, 1972; McSaveney, 1972; Bones, 1973; Yair and Klein, 1973; Knoblich, 1975; Yair and Lavee, 1976), or they focus on the movement of rock debris to, on, and from the surface and relate this back to slope form (e.g. Stevenson, 1945; Rapp, 1960; Caine, 1969; Gardner, 1969; Luckman, 1971; Chandler, 1973; Gerber and Scheidegger, 1974; Kirkby and Statham, 1975; Carson, 1977; Church *et al.,* 1979). Only a few (Fisher, 1952; Dylik, 1960; Molloy, 1964; Bruckl *et al.,* 1974; Harris, 1975; Wasson, 1979) have considered the characteristics of the deposits beneath the surface layer.

In New Zealand, screes mantle many square kilometres of alpine and subalpine terrain, a great deal of which lies below timberline. This study, expanding on earlier work by O'Loughlin (1965), examines the hydrology of scree slopes from the standpoints of water available for tree growth and runoff response of scree basins. The specific objectives are to:

1) define the hydrological characteristics of deposits from a number of morphologically different scree slopes,
2) define the relationships linking slope form (easily identified from air photos) to type of slope deposits,
3) evaluate, from a hydrological standpoint, the suitability of scree slopes for afforestation, and
4) infer the likely hydrological responses of mountain catchments mantled with scree slopes.

THE FIELD AREA

The Craigieburn Range is situated at 43° 10′S. Lat.,, 171° 40′E. Long. about 90 km northwest of Christchurch and about 35 km southeast of the Main Divide of the Southern Alps (Fig. 1). It is a young, elongate, mountain block having a NE-SW orientation and fault-bounded to the NW and SE. The landscape has been dissected by glacial and fluvial erosion and vigorously modified by periglacial processes. Today the slopes of the range are extensively mantled with screes (Fig. 2) and many screes are still actively accumulating. This study was carried out at the northern end of the range, where the main ridge varies between 1700 m and 2000 m elevation and a wide variety of scree-slope types occur.

Bedrock in the Craigieburn Range consists almost entirely of the severely deformed and slight metamorphosed sedimentary rocks of the Torlesse Group (Gregg, 1964). These comprise massive, well-indurated sandstones, siltstones (argillites), and occasional beds of volcaniclastic sediments. All the rocks are pervasively fractured and jointed, although not very weathered chemically. Bedrock outcrops in the range have been extensively loosened by frost action and can be very unstable.

Weakly to strongly developed forest and grassland soils are found

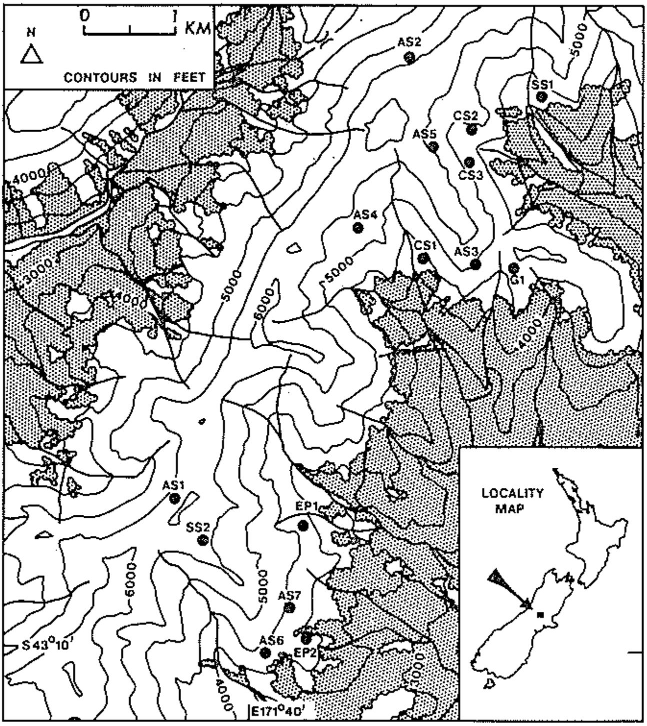

FIG. 1—Locations of screes studied in the Craigieburn Range.

where vegetation is or has previously been established. Parent material may be weakly weathered bedrock, scree, colluvial deposits, eolian deposits, or glacial drift. These soils have been mapped (N.Z. Soil Bureau, 1968; Wilde, 1974) as alpine steepland soils and high country yellow-brown earths (Cryorthents, Dystrochrepts, and Cryochrepts) and they display variable depth, texture and structure. Most of the better developed soils can be described as friable silt loams, commonly stony, which are extremely susceptible to frost lift and wind erosion when unvegetated.

Forests on the flanks of the range are composed almost exclusively of mountain beech *(Nothofagus solandri* var. *cliffortioides),* extending from the valley floor to timberline at 1370 m elevation. Above timberline, snow-tussock grasslands (predominantly *Chionochloa pallens* and *C. macra)* may extend up to 1850 m. Screes themselves are usually unvegetated except for plant communities on soil pedestals and for a few plants that are specially adapted for life on unstable scree slopes (Fisher, 1952).

Climate in the field area (McCracken, 1980) is dominated by the westerly flow of moist air from the Tasman Sea, but the higher ranges to the west exert a strong rain shadow on the Craigieburn Range. At a weather station at 1550 m elevation, the mean annual air temperature is 3.8°C,

FIG. 2—Oblique aerial photo of the southern end of the Craigieburn Range showing extensive development of scree slopes on rock avalanche scar. A number of different types of screes can be distinguished. Note also the large lobe of debris-flow deposits in the lower left centre. (N.Z. Forest Service photo by J. H. G. Johns, ARPS)

with means for the warmest month (February) and the coldest (July) at 9.7°C and —1.4°C respectively. Frosts occur regularly through the year and summer periods when the ground is free of frost average only 17 days. Mean annual precipitation at this elevation is at least 1800 mm—an estimate because of the unknown rain-gauge catch efficiency for snow. Precipitation is distributed fairly evenly throughout the year with roughly 35% of it falling as snow (O'Loughlin, 1969). Mean annual daily wind-speed is 2.7 m/s, but gusts in excess of 67 m/s (240 km/h) have been recorded regularly at several exposed alpine sites.

SCREE SLOPE FORM AND DEPOSITS

Slope Forms

Based on their large-scale geometry, the scree slopes of the northern Craigieburn Range can be divided into three primary *slope forms:* (1) sheets, (2) cones, and (3) gullies (Fig. 3). *Surface morphology* refers to patterns of microtopographic features, such as fluting and hummocks, imposed on the main slope forms. *Surface texture* of the scree slopes, particle size of the surface material, may be coarse—mostly boulders

FIGURE 3a

FIGURE 3b

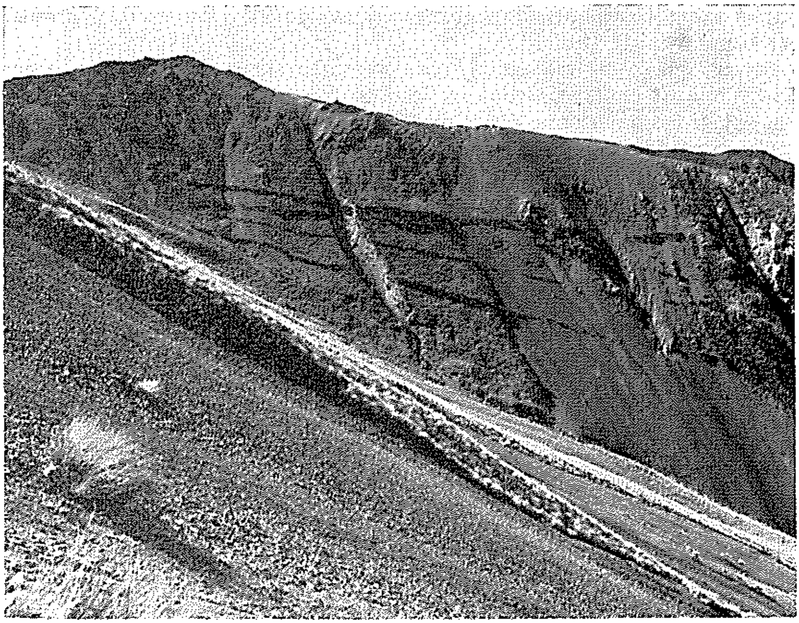

FIGURE 3c

FIG. 3—Three basic forms of Craigieburn scree slopes: a) *Scree sheet*—island of vegetation visible in middle distance; b) *Scree cone*—fresh debris-flow deposits on scree-slope surface (N.Z. Forest Service photo by J. H. G. Johns, ARPS); c) *Scree gully*—three examples of varying ages on far slope (dark horizontal bands are trial plantings of pine trees).

(256 mm), medium—mostly cobbles (64-256 mm), or fine—mostly pebbles (4-64 mm). The basic form categories, as well as surface morphology and texture, are readily distinguishable on air photos. Classification of a particular slope, however, may be complicated, as different forms, morphologies, and textures commonly grade from one to another on a single slope.

Scree sheets blanket the slope, imposing no major topographic highs or lows (Fig. 3a). They can be so extensive as to include whole cirque basins or they can be small irregular patches of scree occurring on vegetated slopes. Surface morphology may include fluting, but most commonly these surfaces are very smooth. Surface textures are usually medium to fine, and in air photos the scree slope surfaces commonly appear streaked (Fig. 2). Extensive scree sheets are common on the western flanks of the Craigieburn Range, where they extend from near the base of the slope to the ridge crest. Rock outcrocks rarely interrupt the smooth surface of sheets; where they do, the outcrops are relatively small. Measured slope angles range from horizontal (on the crests) to 33°; longitudinal profiles are usually fairly straight.

Scree cones are transversely convex scree slopes that usually occur downslope of chutes or couloirs leading from large rock outcrops, and fan out in the downslope direction (Fig. 3b). Adjacent multiple cones may coalesce to form broad undulating surfaces that approach scree sheets in form (Fig. 2). Surface morphology may include fluting and hummocks, but these features are more common toward the bottom of the slope. Surface textures range from fine to coarse. Slope angles measured in the study area vary from 27° to 35° and longitudinal profiles tended to be slightly concave, often with a pronounced coarsening of debris at the toe of the slope.

Scree gullies are gravel-mantled, elongate concavities eroded longitudinally into the slope (Fig. 3c), often cutting into older scree slope deposits.

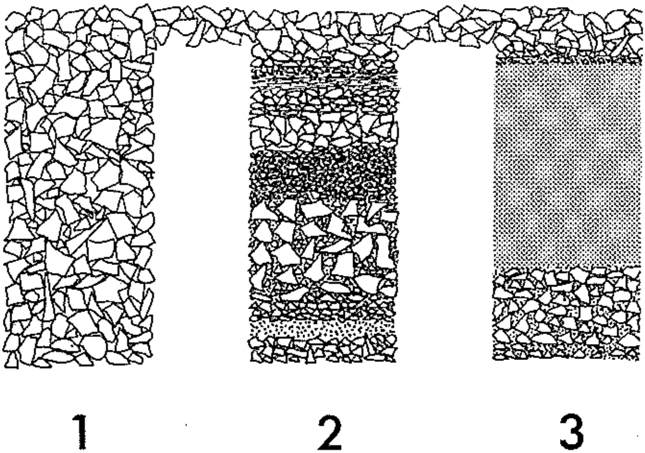

FIG. 4—Schematic profiles of the three basic categories of slope deposits encountered on north Craigieburn scree slopes:

1) *Openwork gravel.* This is an unstratified deposit of fairly angular fine, medium, or coarse gravel. Only a trace of fines are present, adhering to the coarse particles.

2) *Stratified gravel and fines.* In these deposits a thin compact layer of fines (a crust when dry) underlies the surface gravel. Beneath this are mixed layers (often with indistinct boundaries) of fine gravel, gravelly sand, and sometimes sand or silty sand.

3) *Buried, truncated soil.* Beneath the surface gravel and "crust" of fines is a well developed, truncated soil that is commonly the B horizon of a mature forest soil. It is characteristically developed in a discrete layer of silt or sandy silt that overlies stratified fine gravels typical of Type 2 deposits.

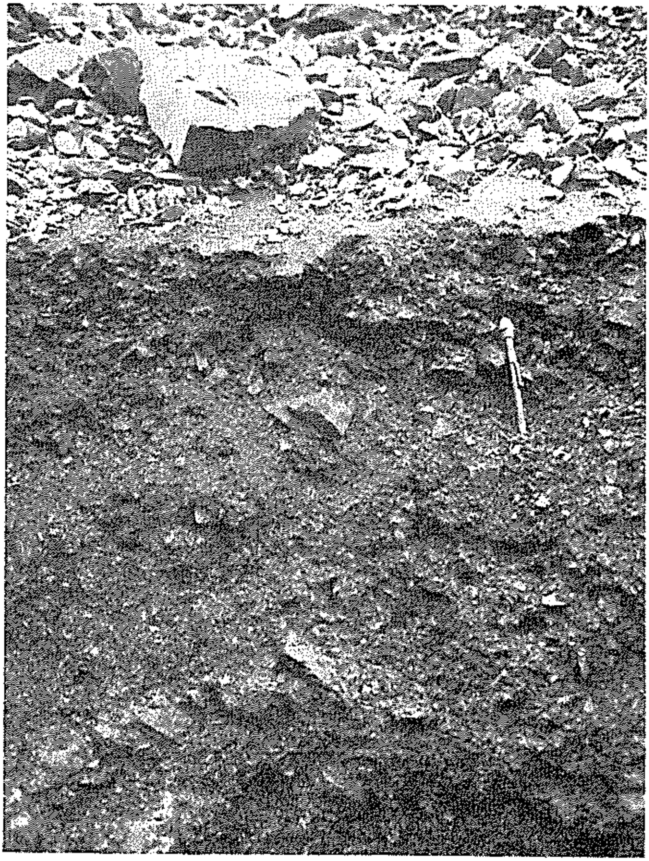

FIG. 5—Vertical soilpit face of a Type 2 scree slope deposit. Note the crust of fines beneath the surface gravel layer and the indistinct, discontinuous layering of gravel.

Gully heads may originate in concave slope depressions, in landslide scars, or at the ends of bedrock chutes. Bottoms may terminate in small debris fans, at the heads of scree cones, or debouch directly into streams. Surface morphology is commonly smooth, but may include fluting or hummocks. Surface texture tends to be fine. The one gully studied is 34° all along its axis.

Slope Deposits

General Features

"A scree is only skin deep" is a phrase that aptly describes many of the north Craigieburn scree slopes. Beneath the scree, visible at the surface, a wide variety of slope deposits occur. Three general categories of deposits could be identified: openwork gravels (Type 1), stratified gravels and fines (Type 2), and buried soil (Type 3) (Fig. 4). Of the sites examined for this study, 77 percent were clearly stratified beneath the surface gravel layer (Types 2 and 3). In these deposits the surface layer of loose gravel was usually 2 to 20 cm thick and was commonly dry (except immediately after a rain), while the underlying deposits were moist. On most scree slopes this gravel layer is "unstable", i.e. particles are easily set in motion by walking across the surface. The thin compact layer immediately beneath the surface gravel in Type 2 and 3 profiles appears to be composed of wind-accreted fines washed by rain down through the scree layer. Once in place it forms a relatively firm, smooth surface on which surface gravel can move downslope. This crust can be seen in Figure 5.

Type 1 deposits are found only in scree cones and medium texture sheets. Type 2 deposits, the most common type in the north Craigieburn Range, are found in cones, sheets, and gullies. Type 3 deposits are confined to scree sheets without upslope source outcrops (usually small patchy areas of scree) and to *stone pavements*—small, irregular areas on slopes that have only a discontinuous layer of surface gravel overlying a truncated soil (Fig. 6). A higher, vegetated, former slope surface usually surrounds the stone pavement or it may be present as raised soil pedestals within the pavement area.

Stone pavements may well be incipient scree slopes. Frost heaving of stones appears to be an active process in bringing gravel to the ground surface. Gravel could also accumulate as a lag deposit, since the bare

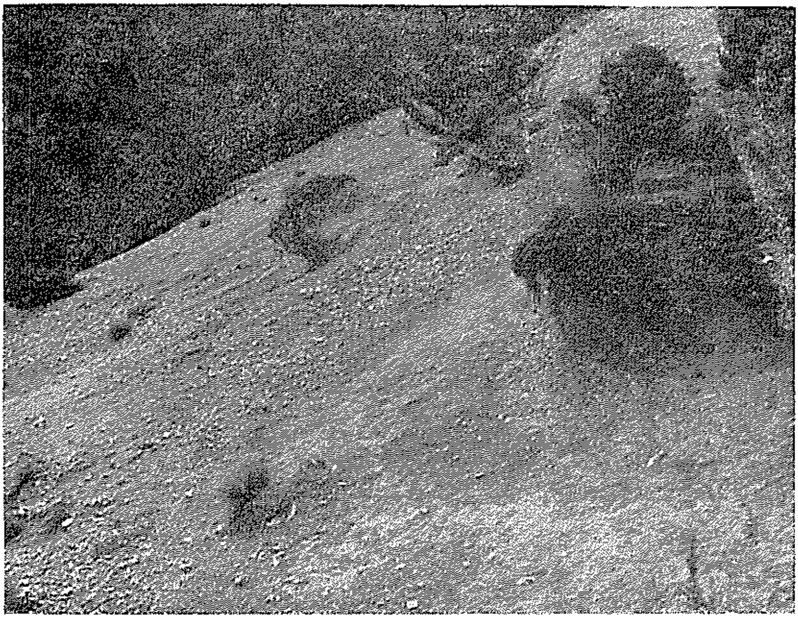

FIG. 6—Stone pavement. Note the discontinuous cover of gravel over the truncated soil.

subsoil is very susceptible to wind erosion in the spring after loosening by needle ice. Furthermore, re-establishment of vegetation on the bare subsoil of stone pavements is inhibited by frost heaving of seedlings in spring and autumn, desiccation in summer, and the combined effect of nutrient deficiencies and near toxic concentrations of Al oxides (Davis a, b, c, in press).

The texture of deposits examined and sampled ranged from cobbley openwork gravels to silts. The majority fell within the boundaries of gravel, sandy gravel, and muddy sandy gravel according to Folk's (1965) classification (Fig. 7), but there appear to be no distinct textural groupings according to slope form. Consistence of moist gravels and sands was uniformly loose; moist silts and silt loams were friable to very friable. Most of the deposits were structureless, although the silty buried subsoils tended to have either a crumb or a platy structure. Porosity was intergranular.

Total thickness of slope deposits was highly variable in the Craigieburns. On the exposed west flank of the range, sheet deposits near the top of the slope were only a few centimetres thick, although deposits thickened downslope. Some scree cones and sheets dissected by streams had deposits that, on the other hand, were tens of metres thick at least. Inspection of cuts revealed that deposits at depth were not significantly different from the top half-metre of deposits accessible to sampling from the surface.

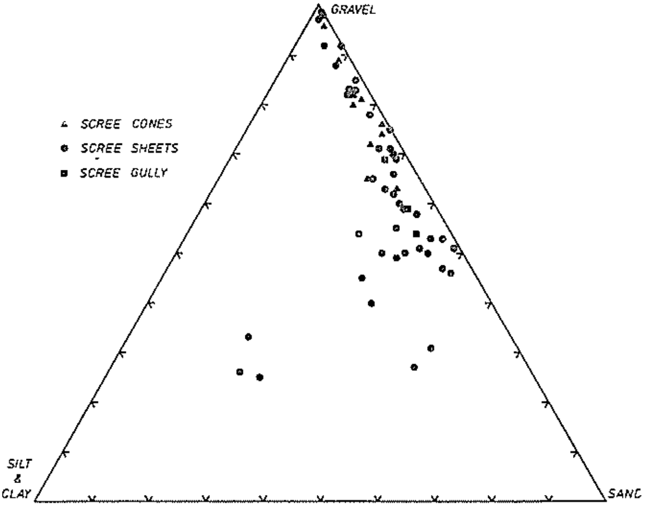

FIG. 7—Triangular grainsize plot showing range of grain-size distributions encountered between sampling sites. Samples were collected at 3 depths: 5-15 cm, 25-35 cm, and 45-55 cm; most, however, are from 5-15 cm.

Physical Characteristics

Sampling:

Fifteen scree slopes were randomly selected from those accessible by road or track at the northern end of the Craigieburn Range. The scree slopes selected covered a wide range of scree-slope types, roughly in proportion to their relative frequency of occurrence in the area (Table 1). On each scree slope, three sites were randomly selected for sampling (except AS7, which had only two), making a total of 44 sampling sites. At four of these sites, four replicate samples were taken within a radius of 1 m to assess the variability at a site. Samples collected for analysis were normally taken from the interval 5 to 15 cm below the surface (the approximate rooting zone for tree seedlings), but at eleven sites, multiple samples were taken at different depths to compare the characteristics of different layers or horizons. In all, 70 slope deposit samples were collected and analysed.

Methods of Analysis:

Mean grain size, sorting, distribution skewness, and bulk density were determined for each sample in order to compare variation at a site, variation between sites on the same scree slope, and variation between scree slopes. Grain-size distributions were determined by dry sieving and pipette analysis, cumulative grain-size distribution curves were drawn, and the following grain-size parameters (Folk, 1965) were determined:

a) Graphic mean grain diameter (M_Z).
b) Inclusive graphic standard deviation (σ_I).
c) Inclusive graphic skewness (SK_I).

TABLE 1—Classification of scree slope selected for slope deposit sampling.

SURFACE TEXTURE		SLOPE FORM	
	Sheet	Cone	Gully
Coarse			
		SS1	
Medium			
	SS2		
	EP1		
Fine	AS1, AS2, AS3, AS4, AS5, AS6, AS7, EP2,	CS3, CS1	G1

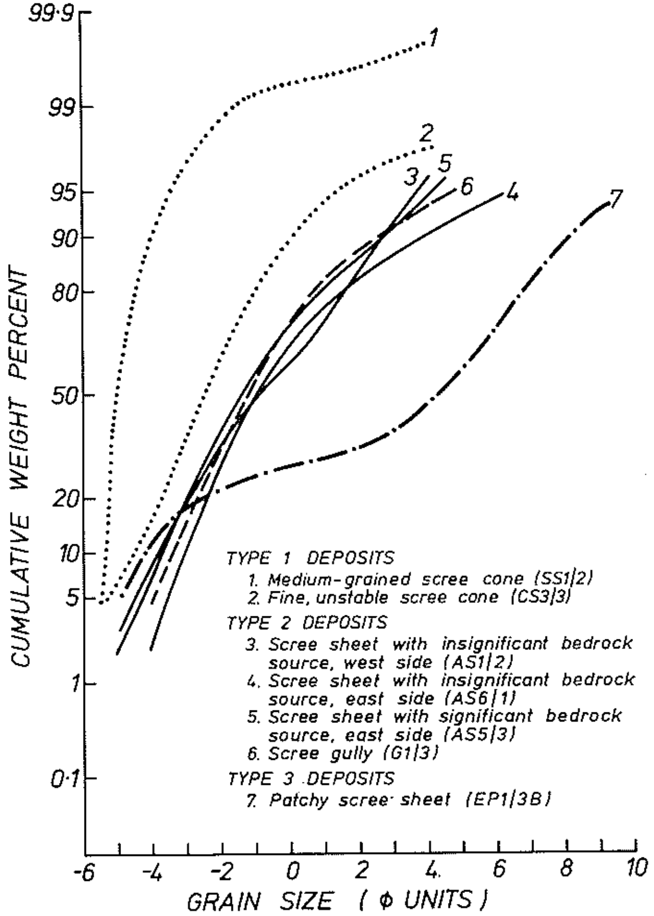

FIG. 8—Representative cumulative grain-size curves showing the variety of deposits encountered on different types of scree slopes.

Grain size categories are gravel (>2 mm), sand (63μm–2 mm), silt (4μm–63μm), and clay (<4 μm). Bulk density was determined in the field by the excavation method (Blake, 1965) and total porosity was calculated from bulk density after particle density of the rock fragments was measured (2.72 g/cm^3).

Results:

An extremely wide variety of particle size distributions was often encountered with depth in the same sampling pit as well as from site to site. The surface layer was always an openwork gravel with only a trace of

TABLE 2—Physical characteristics of the top 5 to 15 cm of slope deposits according to scree slope type. Parameters of Folk (1965).

Scree slope Type	Sample Size	Mean particle Size, M_z (φ units)	Degree of Sorting, σ_I (φ units)	Skewness, SK_I (φ units)	Total Porosity, n_t (%)
Scree Cones, fine surface texture	12	—2.53±0.61	1.61±0.64	0.19±0.16	40.00± 8.67
Medium textured Scree Slopes (Cones and Sheets)	6	—2.74±1.88	1.29±0.70	0.21±0.21	45.00± 4.58
Scree Sheets, fine surface texture					
West side, small source outcrops	7	—0.39±1.50	2.82±0.79	0.27±0.25	43.17± 8.82
East side, small source outcrops	11	—1.16±0.67	2.44±0.70	0.35±0.12	45.55±11.70
East side, large source outcrops	9	—1.61±0.75	2.38±0.32	0.37±0.10	44.50± 5.15
Small, patchy sheets	8	—1.39±1.26	2.39±0.58	0.48±0.15	52.25± 3.88
Scree Gullies, fine surface textures	3	—1.16±0.27	2.33±0.26	0.33±0.09	49.00± 5.20

finer fractions. Most of the samples collected were partially or totally below this layer. The coarsest deposits encountered at the 5–15 cm depth were on the medium textured scree cone, SS1, which had 99% gravel, 1% sand and a mean grain diameter of 32 to 64 mm for the three sampling sites. The finest deposits were silt-loam subsoils encountered at screes EP1 and EP2. Site EP1/3 for example, had 26% gravel, 23% sand, and 51% silt and clay, and it had a mean grain diameter of 0.15 mm. Figure 8 shows cumulative grain-size curves for various scree-slope types.

Sorting of the deposits ranged from "poorly sorted" to "very poorly sorted", according to Folk's (1965) classification, and skewness ranged from "fine skewed" to "strongly fine skewed" (Table 2). Total porosities ranged from around 40% for poorly sorted gravels to over 50% for silt-loam subsoils (Table 2). Virtually all deposits were in a relatively loose state of packing.

Relation Between Slope Form and Nature of Deposit

The primary reason for classifying scree slopes was to test whether any relationships exist between scree slope form (which is discernible on air photos) and the physical character of the deposits on the slope (which control the hydrological response). To determine this, analysis of variance was used to show whether means of the measured physical parameters of deposits were significantly different between scree slopes of different types, based on slope form and surface texture. Two levels of hypothesis testing were carried out. The first was to test for significant differences (at 0.05 level) in parameter means between different scree slope types. Parameters

TABLE 3—Comparison of parameter variation at a site with variation on the scree slope. Variation defined as ±1 standard deviation.

Scree Slope/ Site	Sample Size	Mean Particle Size, M_z (φ units)	Degree of Sorting, σ_I (φ units)	Skewness, SK_I (φ units)	Total Porosity, n_t (%)
AS3 mean	3	—1.50±0.32	2.23±0.25	0.34±0.05	46.33± 8.62
AS3/ replicates	4	—1.52±0.37	2.63±0.23	0.33±0.08	42.25± 4.27
AS6 mean	3	—1.49±0.98	2.06±0.68	0.45±0.03	57.33± 7.77
AS 6/1 replicates	4	—0.63±0.40	2.53±0.25	0.38±0.08	43.75±19.31
EP2 mean	3	0.18±1.08	3.16±0.63	0.46±0.05	50.00± 4.00
EP2/1 replicates	3	—0.86±0.21	2.33±0.17	0.48±0.16	50.50± 2.89
CS2 mean	3	—2.48±0.28	1.45±0.41	0.35±0.11	—
CS2/1 replicates	4	—3.11±0.59	0.94±0.19	0.15±0.20	—

tested were total porosity, mean grain size, degree of sorting, and skewness. The second level broke down the large sheet category into three subcategories based on slope aspect and proximity to bedrock outcrops, and differences between these groups were tested. One-way analysis of variance was carried out, and the degree of variation between means was evaluated using a multiple comparison test, Duncan's Multiple Range Test (Malik and Mullen, 1973) (see appendix).

Significant differences (at the 0.05 level) do exist between the identified scree slope types. Deposits on cones and medium textured sheets are significantly coarser than other regular sheet deposits. Within the sheet category, those scree slopes on the east side of the range having significant bedrock outcrops upslope had significantly coarser deposits than west-facing sheets without major upslope outcrops. This was the only significant difference between the sheet subcategories. Cones and medium textured sheets are also significantly better sorted and significantly less fine-skewed than the other sheet deposits. In terms of total porosity, patchy sheets with their Type 3 deposits were significantly more porous than either the fine textured cones or the other fine textured sheets. Scree gully deposits were intermediate in these parameters between cones and sheets but were usually not significantly different from either.

These results should, however, be seen in the light of variation of parameter means at a site. On four scree slopes (AS3, AS6, EP2, CS2) standard deviation of parameters measured at the three sampling sites on each slope were compared to standard deviations of four replicate samples from one site on each slope (Table 3). In almost half the cases the variation at a site was greater than variation between sites on the same scree slope, implying a high degree of localised variation in these deposits.

HYDROLOGICAL CHARACTERISTICS OF SLOPE DEPOSITS

One site from each studied scree slope plus three additional sites (18 in total) were selected for analysis of a variety of hydrological characteristics at the 5 to 15 cm depth. Seven additional sites on a patchy scree sheet

TABLE 4 Porosity, moisture retention characteristics, and saturated hydraelic conductivity of scree slope deposits from sample sites. Conductivity methods are indicated as either CHP (constant-head permeameter) or DT (dye tracer) and as either D (disturbed) or U (undisturbed). Stars indicate values in excess of 100 cm/h.

SCREE TYPE		SITE	DESCRIPTION	BULK DENSITY D_b (g/cm³)	METHOD	SATURATED HYDRAULIC CONDUCTIVITY (cm/h)	TOTAL POROSITY, %		MACRO-POROSITY (% 0.06 mm repacked)	MACRO-POROSITY / TOTAL POROSITY	FIELD CAPACITY (% of dry wt)	PERMANENT WILTING POINT (% of dry wt)	AVAILABLE WATER CAPACITY (% of dry wt)
Form	Surface Texture						(Field Sample)	(Repacked) Sample					
SCREE CONES	fine	CS1/1	coarse sand and fine gravel	1.73	CHP-D	6	33	41	33	0.80	5.2	0.9	4.3
	fine	CS2/3	fine gravel	1.55	CHP-D	85	—	39	34	0.87	3.0	0.3	3.3
	fine	CS3/1	fine gravel	1.65	CHP-D	73	39	39	32	0.82	4.4	0.4	4.0
	fine	CS3/2	fine gravel	1.75	CHP-D	73	35	26	19	0.73	4.3	0.7	3.6
	fine	CS3/3	fine gravel	1.65	CHP-D	79	34	21	20	0.95	0.6	0.6	0
	medium	SS1/2	medium gravel	1.44	CHP-D	*	—	50	50	1.00	tr	tr	0
SCREE SHEETS													
West Side — Insignificant Source Outcrops	fine	AS1/1	stony silt loam	1.69	CHP-U	34							
	fine	AS1/3	stony sandy silt	1.51	CHP-U	7							
	fine	AS1/2	stony silty sand	1.50	CHP-D	21	46	43	28	0.65	9.1	2.3	6.8
	fine	AS2/2	stony silty sand	1.51	CHP-D	67	38	31	26	0.84	3.0	—	—
East Side — Insignificant Source Outcrops	fine	AS4/1	gravel	1.52	CHP-D	*	42	36	25	0.69	7.2	1.6	5.6
	fine	AS6/2	sandy gravel	1.62	CHP-D	84	51	32	30	0.94	4.1	0.9	2.9
	fine	AS6/2	sandy gravel	1.55	CHP-U	21							
	fine	AS7/1	stony sand	1.62	CHP-D	38	38	21	13	0.62	5.7	2.7	3.0
	fine	AS7/2	sandy gravel	1.71	CHP-D	74	49	38	25	0.66	8.2	1.9	6.3
	medium	SS2/1	stony sand	1.61	CHP-D	82	49	29	22	0.76	4.4	—	—
East Side — Significant Source Outcrops	fine	AS3/2	coarse sand and fine gravel	1.62	CHP-D	*	48	30	25	0.83	3.3	0.7	2.6
	fine	AS5/2	stony sandy loam	1.38	CHP-D	9	46	36	27	0.75	5.5	1.5	3.9
Small, Patchy Sheets	fine	EP1/3	fine silty gravel	1.56	CHP-D	63	54	37	13	0.35	15.1	3.6	11.5
	fine	EP1/3	fine silty gravel	1.19	CHP-U	139							
	fine	EP1/1	sandy gravel	1.40	CHP-U	188							
	fine	EP2/1	sandy fine gravel	1.51	CHP-D	80	51	36	22	0.61	9.3	2.8	6.5
	fine	1A1	stony silt	0.72	CHP-U	32							
	fine	1A2	stony silt	0.80	CHP-U	9							
	fine	1D	stony silt	1.28	CHP-U	27							
	fine	1AA	silty gravel	1.32	DT-U	1104							
	fine	1B1	silty gravel	0.90	DT-U	424							
	fine	1B2	silty gravel	1.31	DT-U	1683							
	fine	1C	sandy gravel	1.18	DT-U	3070							
	Vegetated Silt		silt	0.73	CHP-U	23							
SCREE GULLY	fine	G1/3	sand	1.62	CHP-D	6	46	34	21	0.62	8.8	2.5	6.3

were sampled for hydraulic conductivity only. Both laboratory and field tests were used to determine the drainage characteristics, water-holding capacity, and saturated hydraulic conductivity of these materials (Table 4).

Water Retention

Two experimental techniques were used to establish the relation between tension and water content in the deposits: (1) the hanging water column method (Vomocil, 1965) with 170 to 220 μm glass beads for tensions from 0 to about 60 cm H_2O (0 to 0.059 bars), and (2) a standard ceramic pressure plate extractor for the 15-bar determinations. Estimates of available water-holding capacity, the amount of water available to plants, were made by subtracting the permanent wilting point from field capacity. Field capacity is the approximate water content of a soil or unconsolidated deposit after initial rapid drainage has occurred, and was here taken to be the water content at 0.049 bars tension, the tension which drains all the macropores—pores larger than 0.06 mm diameter. Permanent wilting point (although different for different plants) is taken to be the water content at a tension of 15 bars. Water held at higher tension is generally unavailable to plants.

The results of these determinations are shown in Table 4 together with calculated macroporosities. Some finer grained deposits have available water capacities as high as 11.5%, while very coarse deposits have no water available to plants at all after initial rapid drainage. Macroporosity as percent of total porosity ranged from 35% to 100%. Highest macroporosities occurred in the medium cone and sheet deposits; lower values occurred in deposits with a higher proportion of fines. Those deposits containing more fines have correspondingly higher available water capaci-

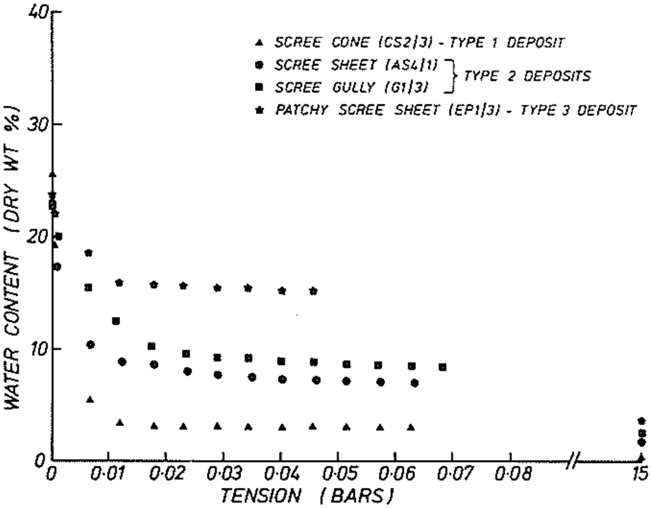

FIG. 9—Soil moisture characteristic curves for 4 samples that show the range encountered for Craigieburn scree slope deposits.

ties. It should be noted that laboratory preparation of the samples resulted in generally higher bulk densities (lower total porosities) than was found in the field. This implies that undisturbed slope deposits are in a very loose state of packing, and that available water capacities of undisturbed samples would probably be slightly higher than these experimental values.

Several representative moisture characteristic curves are shown in Figure 9. After the initial rapid drainage, water content changes only very slowly with increasing tension. As in the case of available water capacity, water retention increases with increasing fines content.

Field Moisture Content

Periodic gravimetric sampling of soil moisture was carried out at 21 different sites on nine scree slopes over one summer (1978-79). Sampling included both the wettest (immediately following heavy rain) and driest (12 days without rain) periods of the season. Soil moisture was measured at three different depths: 5-15 cm below the surface, 25-35 cm, and 45-55 cm (where possible). Samples were collected, sealed in airtight containers and returned to the laboratory where they were weighed, oven-dried, and reweighed. Replicate sampling revealed variation at a site to be about ±0.5% (by weight) in water content, which appeared to be primarily due to local variation in grain size distribution.

Field water contents ranged from complete saturation of some samples immediately after rainstorms to "dusty" dryness of the surface gravel after a number of days of hot sun and dry northwest winds. However, the material beneath the surface gravel held considerable moisture even under the driest conditions. It appears that the surface gravel acts as a stone "mulch"—a barrier that breaks the capillary transmission of soil moisture

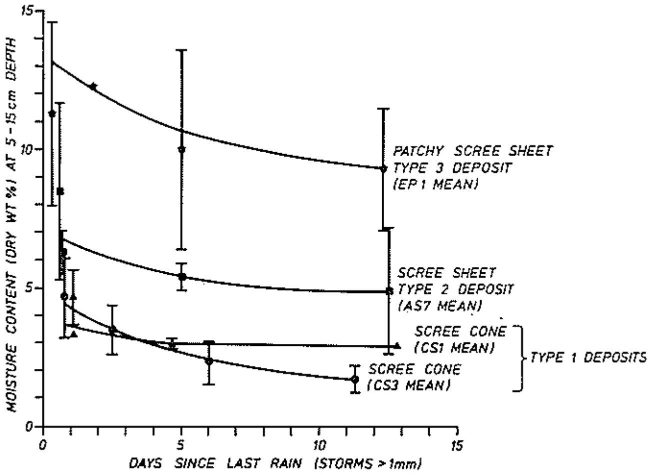

FIG. 10—Change in gravimetric soil moisture with time since last rainfall. Samples were averaged to smooth variations caused by variability in grain size.

to the ground surface, thus greatly slowing the rate of evaporation from the slope deposits. The mean changes in soil moisture content, below this barrier, both with time since the last rain and with depth, are shown in Figs 10 and 11 for several relatively homogeneous deposits. Values were averaged to smooth out the variation caused by local fluctuations in grain size distribution, and the error bars are therefore quite large. Even greater variations in moisture content were encountered in the more stratified deposits. These examples, at least, provide a sense of how soil moisture

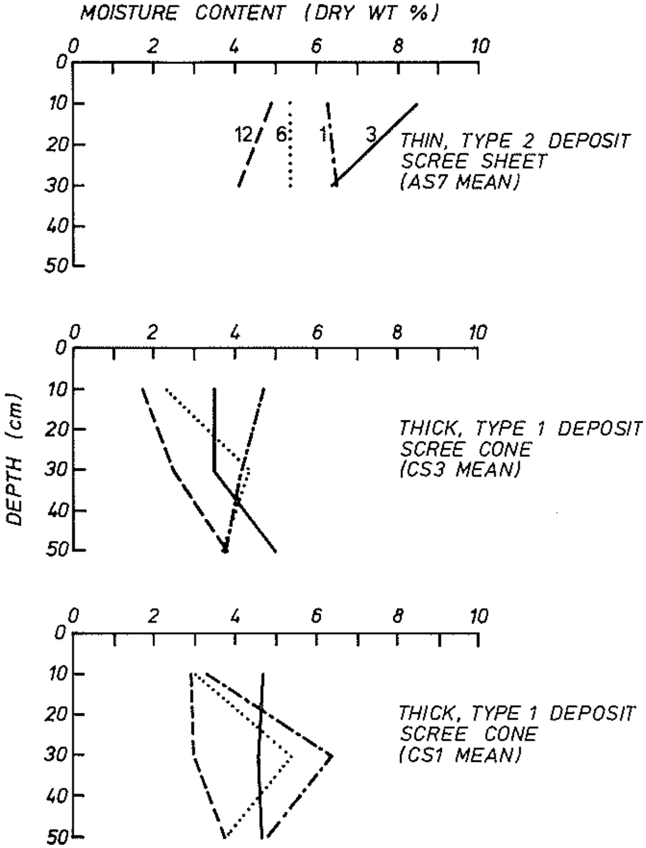

FIG. 11—Change in gravimetric soil moisture with depth. Only sites with homogeneous deposits are shown. Although not indicated, error bars are about ±1.5 percent. Days since last rain (>1 mm) are shown in parentheses for the different curves. The curves labelled "3" (solid lines) are for samples that had also received a very light rain at sites AS7 and CS1 only hours before sampling.

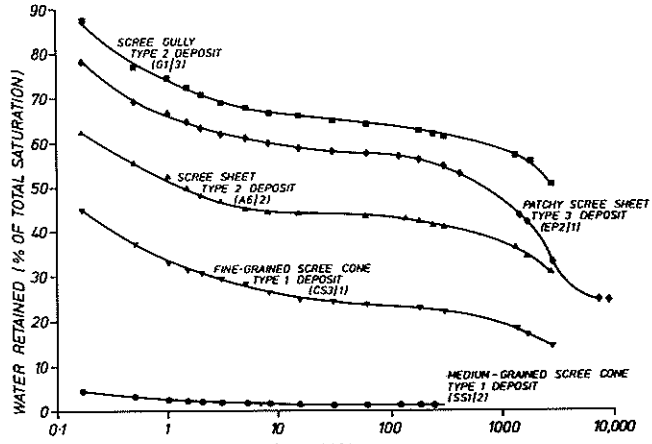

FIG. 12—Time rate of free drainage for representative samples from different scree slope types.

changes with time and with depth when grain size is not a major variable.

A curvilinear decrease in moisture content with time following rain was found for each deposit (Fig. 10). Although coarser deposits are drier in absolute terms, comparison of Fig. 10 with the water retention data (Table 4) reveals that, after 11 or 12 days without rain, the deposits at 5 to 15 cm depth are still well above the permanent wilting point and would remain so for some time. The greatest fluctuations in moisture content occur in the 5-15 cm zone, just below the surface gravel layer, whereas moisture content is more constant at the 45-55 cm depth in CS1 and CS3 (Fig. 11). The shallow deposit of AS7 shows larger fluctuations at depth.

Free Drainage

Free drainage tests were undertaken to determine drainage characteristics of the slope deposits. They are not quantitatively precise tests, however, because of significant boundary effects and because the samples are disturbed. Nevertheless, qualitative comparisons between deposits can be made from them.

The disturbed samples, repacked in 10 cm diameter cylinders with screened bottoms, were saturated and weighed. The samples were removed from their water bath and weighed at intervals while they drained freely. Between weighings the cylinders rested on a sloping, slightly porous surface. Evaporation from the wetted surface probably exerted a slight capillary suction on the sample. After the final reading, remaining water content was obtained by oven drying and reweighing the samples.

Representative drainage curves for the different deposit types are shown in Figure 12. In general, all samples drained very rapidly for the first 15 minutes. During this initial rapid drainage, between 28 and 98 percent of the total water content was lost (mean 51.5±16.8 percent). Over the next

24 hours, between 0.4 and 15.1 percent of the total was lost (mean 10.3± 3.8 percent). Free drainage continued for as long as 5 days, and the amount of water released during the slow "base flow" was, in some cases, almost as much as during the initial rapid phase of drainage. These numbers suggest that, despite the apparent coarseness of the deposits, and despite the slight capillary suction applied to the draining samples by the porous surface they rested on, a significant volume of runoff is retained in scree slope deposits to be slowly released as baseflow to mountain streams.

Permeability

Two methods were used to measure the saturated hydraulic conductivity of the scree slope deposits: a) laboratory determinations on disturbed and undisturbed samples using a constant-head permeameter (Lambe, 1951), and b) field determinations on undisturbed deposits by timing the movement of a dye tracer. For the second method, trenches were dug down to an impermeable horizon upslope and downslope of an undisturbed block of soil. The upslope trench was filled with water and kept filled. Once steady saturated flow emerged from the face of the downslope trench (about 1 metre downslope), a concentrated solution of dye was poured into the upslope trench and the time taken for the dye to strongly colour the outflow from the lower face was measured. The permeability coefficient was then calculated using Darcy's Law. The two methods are not strictly comparable however, because of possible anisotropy in the deposits. Permeameter tests on undisturbed samples measure vertical conductivity, whereas the dye-tracer technique measures conductivity parallel to the slope.

The results of these tests are summarised in Table 4. Values of the lab tests ranged between 10 and about 100 cm/h, but 100 cm/h was the upper limit of the apparatus when 10 cm diameter sample holders were used. It is estimated that the coarse openwork gravels had conductivities in excess of 10,000 cm/h (Dunne and Leopold, 1978). Dye-tracer tests through fine gravels with some sand and silt in the interstices yielded conductivities as high as 3000 cm/h. Undisturbed silt-loam subsoils, in contrast, had conductivities ranging from 9 to 32 cm/h, about the same as the value obtained for a vegetated silty soil, included in the table for comparison. Saturated conductivities for scree sheets without significant source outcrops upslope were also very similar.

It should be noted that when the same sites were sampled for both disturbed and undisturbed samples (EP1/3 and AS6/2, Table 4), the replicates were not very similar. When taken as order of magnitude indications of permeability, however, these results should be adequate.

Infiltration capacities were not measured, although overland flow on one scree slope (CS3) was observed during an especially intense thunder shower. Rilling and gullying on many scree slopes suggest that infiltration capacities are regularly exceeded.

DISCUSSION

Implications for Afforestation

The soil moisture regime on most Craigieburn scree slopes (Type 2 and

3 deposits at least) appears to be adequate for tree growth, with available water capacities ranging up to 11%, depending on grain size. Openwork gravels (Type 1 deposits), however, would not retain enough moisture. A number of successful planting trials of *Pinus mugo* and *Alnus viridis* on scree sheets and cones has verified that trees will grow in some scree slope deposits (Benecke, 1970; Benecke *et al.*, 1978), although nutrient deficiencies may ultimately be limiting. Key factors to this moisture retention appear to be the presence of sufficient fines and the often mobile gravel layer at the surface, which acts as a mulch to hold moisture in the underlying deposits. The absence or removal of this layer would accelerate desiccation of the soil, especially in shallow scree deposits. Further advantages of the surface gravel layer are that it inhibits frost lift of seedlings and insulates the underlying deposits from extreme summer temperatures which may rise to as high as 45° to 50°C during the day (Fisher, 1952).

This same surficial gravel also presents problems for tree seedlings because of its instability. Downslope movement of gravel can abraid seedlings or bury them before they are vigorous enough to withstand this particle movement. On fine-grained screes, "sand blasting" by wind-blown rock fragments is extremely damaging. Unpublished results from the Forest Research Institute (U. Benecke, pers. comm.) have shown that 1.3 m high stakes placed upright on the surface of scree slope CS1 were completely stripped of four layers of paint and several millimetres of wood along their entire height on the upwind side after only 18 months.

Implications for Runoff Response

The hydrological response of scree-mantled alpine watersheds cannot be predicted solely on the basis of the physical and hydrological properties of the scree slope deposits studied here. This is because of the variable distribution of scree types among alpine basins, the high degree of variability in the properties of the deposits, both areally and with depth, and the great variation in thickness of the deposits. The response of any catchment also depends on such additional factors as storm size, the length and gradient of the slopes, and the relative amount of deep percolation into bedrock.

Relative responses, however, may be interpreted on the basis of physical and hydrological properties, assuming that the material at depth in the thicker deposits is similar to that sampled near the surface. On all scree slopes, water loss through evapotranspiration will be minimal because little or no vegetation is present, and the gravel mulch on the scree surfaces greatly reduces surface evaporation by inhibiting capillary moisture rise to the ground surface and by protecting the fines below from heat and wind. Evaporation from scree slopes in the Soviet Union has been measured to be about 4-5 times less than from adjacent meadows (Golubtsov, 1976).

The water-holding capacity of openwork scree gravel is very low, due to the small surface-area to volume ratio. Scree and talus deposits composed exclusively of such gravels should drain rapidly, delivering runoff rapidly to streams or to ground-water storage. The free drainage tests (Fig. 12) show, however, that most of the scree slope deposits in the Craigieburns do not respond in this way. Instead, Type 2 and Type 3 deposits can retain a large percentage of infiltrated water, releasing it slowly to baseflow rather than to stormflow. Watersheds having thick accumulations of such deposits should have small storm runoff responses if infiltration capacity is not limiting. Silt-rich Type 3 deposits may, on the other hand, have sufficiently low infiltration capacities to cause significant overland flow during large storms. Infiltration can be further hindered by frozen surface layers during winter and spring, and by the infiltration-impeding effect of the surface gravel layer (Yair and Lavee, 1976). Commonly encountered rilling and gullying on slopes with Type 3 deposits, especially stone pavements, confirms the occurrence of frequent overland flow. Slope areas mantled in such deposits should show a storm-flow dominated hydrological response.

Rate of runoff production aside, Craigieburn scree slopes should generally have high water yields in proportion to rainfall input. Runoff ratios from the Torlesse Stream catchment (a comparable watershed in the nearby Torlesse Range, nearly half of which is mantled with scree) are very high. Reported water yields are 80% to 90% of precipitation (Hayward, 1980). This compares with 2% to 34% for pastoral and forested catchments in the eastern U.S. (Hewlett and Hibbert, 1967) and with about 50% for forested catchments in Westland (Pearce, 1980).

CONCLUSIONS

Beneath the surface layer of scree gravel, a wide variety of slope deposits are encountered on north Craigieburn Range scree slopes. The physical and hydrological properties of these deposits can be roughly estimated from slope form, coupled with surface texture—two parameters readily discernible from air photos.

Scree cones and some sheets (particularly medium textured, relict sheets and sheets beneath large rock outcrops) usually comprise thick deposits of openwork gravel (Type 1 deposits), having few fines and little or no stratification. They drain extremely rapidly due to the large pore spaecs between particles. Saturated hydraulic conductivities, in most cases, probably exceed 10,000 cm/h and virtually no water remains in these gravels that is available to plants after initial drainage occurs.

Scree sheets without large outcrops upslope, as well as some cones and gullies, characteristically have stratified colluvial and eolian slope deposits beneath the scree layer (Type 2 deposits). They range in texture from fine gravels to silty sands. Although these deposits show initial rapid drainage, they retain a relatively large percentage of infiltrated water (30 to 70% of total saturation) that is available to plants and is later released as baseflow. Saturated hydraulic conductivities are generally in the range of about 100 to 3000 cm/h.

Some scree sheets, particularly the small patchy sheets and stone pavements that occur on otherwise vegetated slopes, typically have a truncated silt-loam soil beneath the surface gravel (Type 3 deposits). This subsoil has a high water retention capacity, but also a relatively low infiltration capacity. Overland flow and surface erosion are relatively frequent occurrences on these slopes. Saturated hydraulic conductivities are on the order of 10 to 100 cm/h.

The thin layer of angular gravel that characterises scree slopes appears to play a major role in scree slope hydrology. When the layer is sufficiently thick it acts as a mulch, insulating the deposits beneath from extreme summer temperatures and acting as an evaporation barrier, effectively interrupting the rise of capillary moisture to the surface. This mechanism, combined with the general lack of vegetation, should result in very low evapotranspiration losses from scree slopes.

Hydrological response of alpine watersheds predominantly mantled with scree slope deposits will depend on many factors including storm size, the relative distribution of scree slope types, thickness of the depoists, length and gradient of slopes, and permeability of the underlying bedrock. On the basis of properties of scree slope deposits measured for this study, runoff responses may range from (1) broad, baseflow-dominated hydrographs with low peakflows and very high runoff ratios for thick Type 1 and Type 2 deposits (i.e. scree cones and some sheets and gullies) to (2) more "flashy" stormflow dominated hydrographs with higher peak flows and lower runoff ratios (higher evaporative losses) for Type 3 deposits (i.e. some sheets, particularly patchy sheets and stone pavements).

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APPENDIX

Results of statistical evaluation of the relation between scree slope type and physical characteristics of scree slope deposits:

Analysis of variance tables and graphical results of Duncan's Multiple Range Test. H_0=no significant difference between means at the 0.05 level.

Abbreviations used: DF (degrees of freedom), SS (sum of squares), MS (mean square), and F (F-statistic).

A. Comparison of different subcategories of scree sheets, all with fine surface texture.

W=West side of range, insignificant bedrock source area.
I =East side of arnge, insignificant bedrock source area.
S =East side of range, significant bedrock source area.

(1) Parameter: n_t (total porosity)

Source of variation	DF	SS	MS	F	Decision
Between groups	2	22.20	11.10	0.13	Accepted H_o
Within groups	22	1943.56	88.34		
Total	24	1965.76			

Duncan's Multiple Range Test @ p=0.05

W *S* *I*
— — — — — — — —

(Connection by continuous dashed line indicates no significant difference.)

(2) Parameter: M_Z (mean grain diameter in phi units)

Source of variation	DF	SS	MS	F	Decision
Between groups	2	5.94	2.97	3.19	Reject H_o
Within groups	24	22.34	0.93		
Total	26	28.28			

Duncan's Multiple Range Test @ p=0.05

S *I* *W*
— — — —
          — — — — —

(3) Parameter: σ_I (sorting coefficient)

Source of variation	DF	SS	MS	F	Decision
Between groups	2	0.86	0.43	1.09	Accept H_o
Within groups	24	9.46	0.39		
Total	26	10.32			

Duncan's Multiple Range Test

S *I* *W*
— — — — — — — —

(4) Parameter: SK_I (skewness)

Source of variation	DF	SS	MS	F	Decision
Between groups	2	0.05	0.02	0.93	Accept H_o
Within groups	24	0.59	0.02		
Total	26	0.64			

Duncan's Multiple Range Test

S *I* *W*
— — — — — — — —

B. Comparison of different categories of scree slope type

C=Scree cones, fine surface texture
S=Scree sheets, fine surface texture
SS=Medium textured screes (cone and sheet)
G=Scree gullies, fine surface texture
P=Small patchy sheets, fine surface texture

(1) Parameter: n_t (total porosity)

Source of variation	DF	SS	MS	F	Decision
Between groups	4	600.38	150.10	2.36	Reject H_o
Within groups	40	2543.26	63.58		
Total	44	3143.64			

Duncan's Multiple Range Test @ $p=0.05$

C	*S*	*SS*	*G*	*P*
—	—	—	—	
		—	—	—

(2) Parameter: M_Z (mean grain diameter in phi units)

Source of variation	DF	SS	MS	F	Decision
Between groups	4	25.47	6.37	5.30	Reject H_o
Within groups	51	61.22	1.20		
Total	55	86.69			

Duncan's Multiple Range Test @ $p=0.05$

SS	*C*	*P*	*G*	*S*
—	—	—	—	
		—	—	—

(3) Parameter: σ_1 (sorting coefficient)

Source of variation	DF	SS	MS	F	Decision
Between groups	4	11.44	2.86	7.37	Reject H_o
Within groups	51	19.79	0.39		
Total	55	31.23			

Duncan's Multiple Range Test @ $p=0.05$

SS	*C*	*G*	*P*	*S*
—	—			
	—	—		
		—	—	—

(4) Parameter: SK_1 (skewness)

Source of variation	DF	SS	MS	F	Decision
Between groups	4	0.50	0.13	4.87	Reject H_o
Within groups	51	1.31	0.03		
Total	55	1.81			

Duncan's Multiple Range Test @ $p =0.05$

C	*SS*	*G*	*S*	*P*
—	—	—		
	—	—	—	
		—	—	—