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Snow Depth Measurement with Terrestrial Photos

Results indicated that the mean snow depth was estimated to within 10 percent of the actual value, and that conventional methods would probably have larger error.

Abstract: *Research into the hydrological effects of afforestation required daily measurements of a shallow and frequently ablating snowpack, preferably without disturbance of the snow surface. A measuring system based on terrestrial photogrammetry was developed; its design and operation with particular reference to choice of sites, equipment, ground control, photography, and photoanalysis are described.*

Introduction

Hydrology is the study of the occurrence and movement of water in all its forms, over and within the Earth's surface. In the United Kingdom considerable knowledge exists on the natural processes of water in its liquid form, but relatively little is known about the most important solid form, snow. This deficiency is largely because the snow season is rarely spectacular, and hence the hydrological significance of snowfall is easily underestimated. However, many of the most damaging floods in the United Kingdom result from heavy rainfall on snow lying on frozen ground (Wolf, 1965), and meltwater from snow may be an important factor in the recharge of aquifiers for water supply.

To gain a better understanding of the occurrence and melting of snow, the first requirement is to estimate its water equivalent. Traditionally this is estimated from a series of manual depth and density measurements taken at set intervals along snow courses —lines laid out within an area such that different topographical features are sampled. This procedure, however, often proves inadequate as large spatial variations in snow depth cannot be adequately detected, due to limitations on time, manpower, and accessibility. Conventional rain gauges, even if heated, are also unsuitable due both to the sampling problem and to gross errors due to drifting induced by air turbulence.

These measurement problems have been encountered in the Institute of Hydrology's investigation of the hydrological consequences of a land use change from grass to coniferous forest in two small catchments at Plynlimon in central Wales. Here, snow tends to fall and ablate completely many times during a winter, and daily measurements are necessary. An additional requirement for frequent spatial measurement ruled out the sole use of either snow pressure pillows (Tollan, 1970) or nuclear counting devices which measure the attenuation by snow of the radiation emitted by buried artificial radioactive sources (Warnick and Penton, 1971). Both methods provide accurate records of the water equivalent of the snow covering the instruments but are too costly to use in large numbers.

Only aerial monitoring of the natural radioactivity of the earth, or the use of photogrammetry from either an airborne or ground based platform, seemed to provide suffi-

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ciently frequent spatial measurements. Monitoring the natural radioactivity of the earth offers substantial advantages (Bissell and Peck, 1973), but would be costly and was not considered sufficiently precise to deal with snow depths typically in the range 10-1000 mm. Similar reasons precluded the use of aerial photogrammetry (Cooper, 1965, and Smith, Cooper and Chapman, 1967). Photogrammetry, using either a tethered balloon platform or a ground-based system, was discussed by Painter (1973), and subsequently terrestrial photogrammetry was chosen as the most likely method for measuring snow depth at Plynlimon. Blyth & Painter (1973) describe the initial snow measurement tests, and the hydrological implications of their success. The tests also enabled definite operational procedures to be established for the day-to-day measurement of snow depth and this paper describes these procedures, with particular reference to the choice of sites, ground control, photography, and photointerpretation.

Choice of Sites

Measurements of snow depth are to be made in an upland area having a valley-hilltop relief of some 100-150 meters. To obtain the greatest incident viewing angle to the ground surface, hillslope sites were generally chosen in preference to the relatively flat valley floors and hilltops, which in any case tend to be unsuitable for photogrammetry due to the presence of long grass and reeds. As most of the valleys are fairly symmetrical in cross section, it was usually possible to establish the camera positions on one side of a valley and photograph the opposite valley slope onto which ground control markers are set.

Photographs are to be taken of each site in late autumn or early spring when vegetation is at its lowest, to enable the ground surface to be accurately heighted; further photographs are taken from the same positions each day that snow remains. The procedure for taking the stereo-paired photographs is relatively simple, as normal photography with a metric camera, mounted on an orientation base, is used. The camera base line is set approximately perpendicular to the opposite valley slope, with vertical camera separation limited by the type of restitution instrument used. Horizontal camera separation is chosen such that the ratio of camera base line to viewing distance does not exceed 1:7 for the sake of accuracy. The orientation base is centered and levelled at one camera position, and a target is centered at the other. Using the orientation facility, a bearing is taken on the target, and the camera is then swung through 90 degrees to face the opposite slope (Figure 1). After taking the photograph, the camera and target are interchanged, and the procedure repeated. Because only one camera is used, the time lag between taking the stereopairs should be kept as short as possible to minimise the possibility of *pseudo-parallax;* this can occur in the reconstructed image due to changing light conditions or wind induced movement of the vegetation during photography. Ideally either a pair of simultaneously triggered cameras should be used, or photography should be conducted on a calm day with fairly constant lighting conditions in order to minimise this effect.

Ground Control

As measurements are to be taken over several years, it is essential that both camera positions and ground control markers are constructed in such a way that no movement occurs. To keep the operational procedure as quick as possible during snow photography, permanent camera plinths bearing simple and precise centering facilities are essential. The plinths used comprise an upper and lower steel triangular plate, joined by three rigidly welded scaffolding poles, suitably treated to prevent corrosion. Each plinth is set in concrete with its lower plate at least 300 mm below ground level and with the upper plate level.

A Wild P32 Terrestrial Camera mounted on a Wild T1A theodolite is used for the snow survey, and several methods of centering this system on the plinths were investigated. After considering the precision, cost, and ease of setting up and transporting the various centering systems, the Wild ball centering method was chosen. This utilizes a steel ball screwed into the base of a GDF4 Tribrach, which fits into a precision bored brass socket, normally set in concrete. For the snow survey work, the sockets were replaced by a similarly bored stainless steel insert, set into the upper plate of the camera plinth (Figures 2 and 3). Repeated centering of the theodolite and camera are possible to within $\pm$ 0.02 mm, and an attachment on the ball allows repeated height fixing. An accurately centered target which locates in the same bore allows complete interchangeability with the theodolite.

The ground control markers are robustly constructed in noncorrosive materials and are varied in size according to their distance from the camera. The pattern on the markers

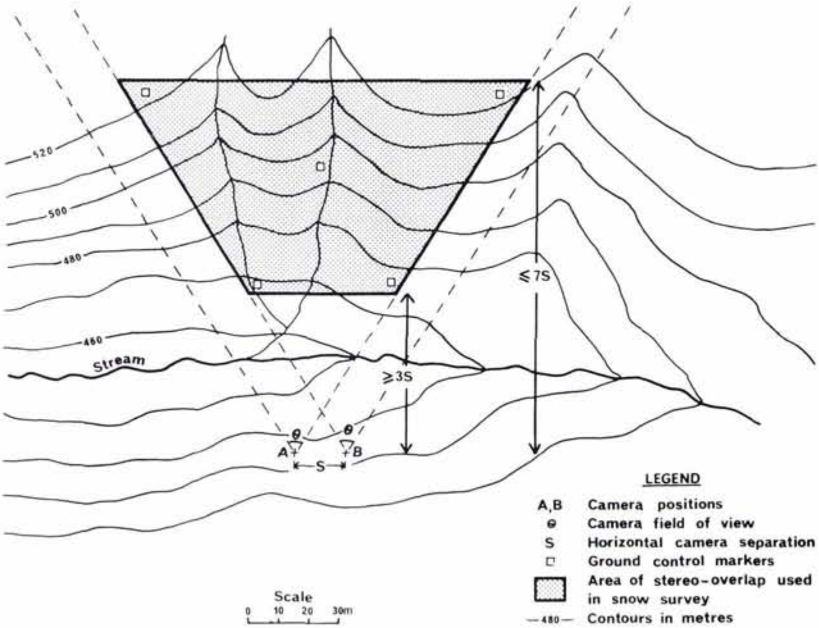

FIG. 1. Generalised plan of typical snow measurement site.

(Figure 3) consists of a central white cross to which black cross hairs are added to aid the accurate location of the ground survey measurements. A black background is used to provide maximum contrast and white squares are inset at each corner away from the edge of the marker. Using this configuration, three squares of different sizes are defined into which the floating mark of the restitution instrument can be accurately fixed, thus reducing the need for a great variety of marker sizes. At the Plynlimon sites, only two sizes of marker, with outside dimensions of 1000 mm square and 500 mm square, were required. Ideally, one of the squares on the marker should appear slightly larger than the floating mark if viewed through the stereo plotting instrument. This size is determined by the formula,

$$A = C\,D/F$$

where A is the side dimension of the square, C is the distance from the camera to the target, D is the actual diameter of the floating mark and F is the focal length of the camera lens. The marker pattern is applied by a silk screen process to alloy sheets. To reduce the effect of wind, the sheets are cut vertically into 100 mm strips which are offset alternately thus allowing the wind to pass through the marker. 50 mm alloy channeling set in concrete is used to locate the targets above the expected snow level (Figure 3).

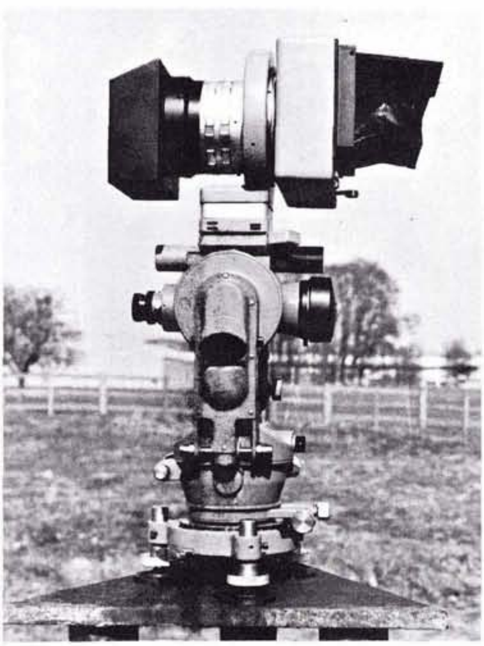

FIG. 2. Wild theodolite and P32 camera accurately centered on camera plinth.

Measurements are taken on the hill slope sites up to a maximum distance of 7× the camera base length, for accuracy, and a minimum working distance of 3× the camera base length is imposed both for accuracy and for operator comfort, as working at closer distances than this was found to be strenuous.

To enable the stereo model to be accu-

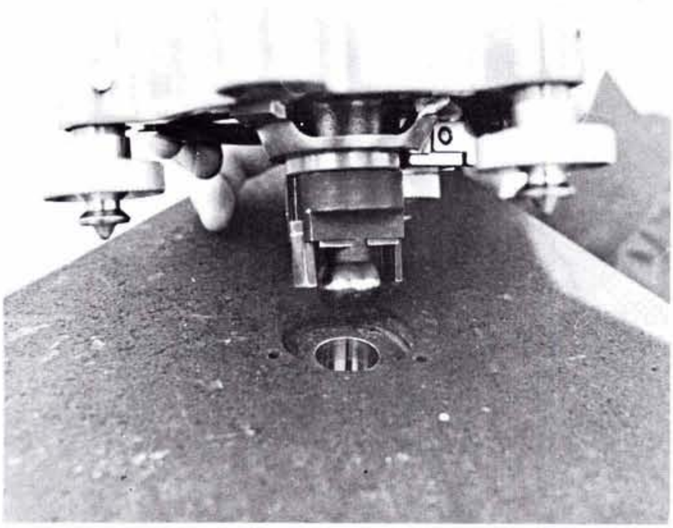

FIG. 3. The Wild ball centering system

rately scaled and levelled in the plotting machine, at least five ground control markers should be set up within the stereo area of each pair of photographs. Although scaling and levelling could be achieved with only four suitably spaced markers (using one as a check) it is considered desirable to have more to guard against the possibility of a target moving or being covered in a snow drift. In general, one marker should be kept in the center of the stereo model, with the others sited towards each corner, though the position of both camera stations and markers should be arranged to suit each site. In some instances, for example, a third camera station is used to increase the depth of the workable area.

The relative orientation of the camera stations and markers was determined by theodolite and an MA 100 tellurometer. In the original feasibility test, the camera stations at A and B in Figure 1, were used to define a three-dimensional, rectangular coordinate system, in which heights were vertical and the eastings and northings planes were horizontal. The origin of the system was assumed to lie 1000 m west, 1000 m south, and 100 m below point B, and the coordinates of each

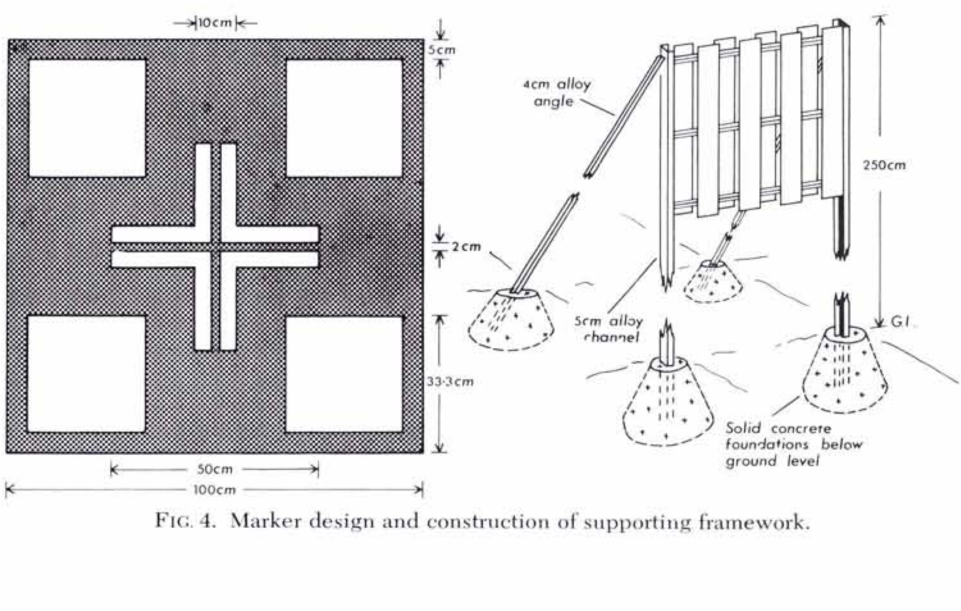

FIG. 4. Marker design and construction of supporting framework.

marker were determined relative to this origin. Similar coordinate systems are being used on all sites and the standard error of all three coordinates of any point is considered to be ± 3 mm. It is important to recognize that the errors of the final values from the photogrammetric process cannot be smaller than the errors present in the control. To check that no significant movement of the ground control has taken place, further surveys should be made shortly before and immediately after the snow season.

Photography

Although more precise cameras are available, the Wild P32 camera was chosen both for its low weight and versatility, and for its good precision:cost ratio. The useful format of the camera is 60 × 80 mm but the principal point of the picture is offset 10 mm relative to the principal parallel to give optimum utilization of the picture format during stereophotography. Either cut film, roll film, or glass plates can be used in the camera, and are pressed against a glass plate bearing fiducial marks to ensure flatness. The 65 mm focal length lens has a resolution greater than 100 lines per mm at its center, and some 70 lines per mm at the edges; the actual camera used in the current work has a very low radial distortion of only ± 1μm. The camera is attached to the theodolite telescope by a quick release lever, and is precisely collimated with the telescope so that its absolute orientation can be accomplished using the theodolite facilities.

One of the main problems envisaged in snow photogrammetry was to place the floating mark of the restitution instrument accurately upon a white surface offering little contrast. Experiments conducted on a simulated snow surface, using a range of films and filters, indicated that there was no single combination which markedly improved the highlight and shadow details of the surface. Subsequent field tests showed that although color film was most suitable for interpreting detail in no-snow photographs, it offered little advantage over monochrome film in snow conditions. As color transparencies were readily available only in film form, a fine-grain monochrome emulsion such as Ilford FP4 on the more accurate glass plates was considered to be most suitable for this precision work, and so this was used for both the snow and no-snow photography.

To give a soft gradation in the image tone of the snow photographs, the film was overexposed by 3 stops compared to the normal setting for the particular film speed, and the subsequent processing time was decreased by 20 percent. This gave the snow a dirty gray appearance which was much easier to interpret, but the resolution was slightly decreased due to the resulting increased grain size. An emulsion which was not fully tested, but which may prove beneficial in this type of photography is Ilford R10, which is a soft panchromatic film with a fairly high resolution; its slow speed may however prove to be a major disadvantage.

In very bright conditions, a polarizing filter was found to reduce glare considerably from the snow surface, whereas an ultra violet filter slightly increased penetration through mist and haze. However, because filters introduce unknown distortions, snow photographs should be taken in cloudy but mist-free conditions, wherever possible.

Photoanalysis and Computation

In analyses to date, the stereo model has been set up in a Zeiss (Jena) Topocart plotter, by orientating and scaling the model to give a best mean fit on the ground control markers; the largest discrepancy in this operation was equivalent to 60 mm on the ground.

A grid of 5 meter squares was constructed in a horizontal plane within the stereo model, and the height of the ground and subsequently that of the snow surface at each intersection, together with a unique point number and a coding digit, were recorded on punched paper tape. The coding digit was used to describe the nature of the surface at that particular grid intersection, from the point of view of the plotter operator. Thus the surface was graded good, average, bad, or impossible to height photogrammetrically. This assessment was made by the operator, according to the ease with which the floating mark could be placed on the ground or snow surface. Surfaces rated typical of each of the three possible grades were chosen, and 20 consecutive height readings were taken at a specific spot on each surface, and the standard errors of the readings at the points were calculated for each group.

The terms *S1* and *S2* in the computer printout (Table 1) are functions of these standard errors for snow and ground measurements respectively, and of the square of the distance of the point from the camera for any particular group. These standard errors do not reflect random errors arising from the ground control or from orientation of the model, nor do they indicate systematic errors from lens distortion, instrument maladjustments or film distortion, but the procedures and equipment adopted have reduced these to a

TABLE 1. FORMAT OF TYPICAL COMPUTER PRINT-OUT OF RESULTS

Plynlimon Test Site
Camera: P32
Photography: 16/2/73 Plates A7 and B7. 1/2/73 Plates A3 and B2

Point	*Z1*	*Z2*	*S1*	*S2*	*Depth*	*Remarks*	*Wt*
34	64.400	64.375	0.053	0.053	0.025		178.1
35	65.138	65.088	0.053	0.053	0.050		178.1
36	65.075	65.05	0.053	0.053	0.025		178.1
37	65.075	64.963	0.025	0.053	0.112		289.5
38	65.362	65.375	0.025	0.025	−0.013	Negative Depth	773.1
39	66.213	66.162	0.025	0.025	0.050		773.1
40	66.875	66.862	0.053	0.053	0.013		178.1
41	66.038	68.162	0.053	0.053	−0.125	Negative Depth	178.1
42	69.737	69.650	0.056	0.056	0.088		159.1
43	61.587	61.312	0.027	0.056	0.275		258.7
44	61.587	61.350	0.027	0.056	0.238	Impossible	0.0
45	62.425	62.575	0.027	4.000	−0.150		0.0

Z1 is elevation of snow surface
Z2 is elevation of ground surface
S1 is standard error of snow surface measurement
S2 is standard error of ground surface measurement
Wt is weighting given to point measurement.

minimum. A weighting equal to $1/(S_1^2 + S_2^2)$ was then allocated to the readings at each intersection, and the average areal snow depth was computed as the mean of the individual weighted depths. A value for S_1 or S_2 equal to 4.000 or 5.000 in the printout was used to denote an impossible point due to, for example, long grass in the no-snow photographs, or mist or glare in the snow photographs.

Where negative depths have been obtained, a statistical criterion for rejection was used; only if the negative depth measured was numerically less than three times the standard error of the depth, was it accepted, otherwise it was given zero weight. Whether these large negative depths should be rejected is arguable, as similar positive errors cannot be easily detected. Statistical analysis is therefore continuing to determine the optimum criterion both for dealing with negative depth measurements, and to establish the minimum number of point readings necessary to give the required areal accuracy.

CONCLUSION

Terrestrial photogrammetry offers a rapid method for gathering large quantities of snow-depth data without disturbing the snow surface, and the analysis of the data can be left until after the snow season if necessary. Results to date indicate that the mean snow depth over an area of 3 hectares can be estimated to within 10 percent of the actual, and that conventional snow courses would offer only a 1 in 4 chance of comparable accuracy.

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