



Teaching and Learning in a Practical Course on Snow Hydrology, Switzerland, 1976-79

Document Version

Final published version

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Braithwaite, R. J. (2001). Teaching and Learning in a Practical Course on Snow Hydrology, Switzerland, 1976-79. *Zeitschrift fur Gletscherkunde und Glazialgeologie*, 36(2000), 159-170.

Published in:

Zeitschrift fur Gletscherkunde und Glazialgeologie

Citing this paper

Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

General rights

Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Takedown policy

If you believe that this document breaches copyright please refer to the University of Manchester's Takedown Procedures [<http://man.ac.uk/04Y6Bo>] or contact uml.scholarlycommunications@manchester.ac.uk providing relevant details, so we can investigate your claim.



TEACHING AND LEARNING IN A PRACTICAL COURSE ON SNOW HYDROLOGY, SWITZERLAND, 1976–1979

By R. J. BRAITHWAITE, Manchester

With 5 figures

SUMMARY

A practical course in snow hydrology was conducted for students in February/March for four years 1976–1979 in seasonal snowcover (Ibergeregg, alpine foothills) and in September 1977 on a glacier (Griesgletscher). In a half-day activity, students dug snowpits to study snow characteristics and measured snow density. They also measured snow depth around the snowpits and measured water equivalent at stakes along 1 km profiles. The data analysis and discussion with students focussed on comparing measurements made in different ways, in different years, and in different profiles. Snow depth in snowpits was found to be significantly greater than average snow depth around the snowpits due to bias in selecting snowpit sites. Snow densities measured by horizontal and vertical sampling showed no significant difference in mean density although individual discrepancies amount to ± 20 to $\pm 41 \text{ kg m}^{-3}$. Snow density on Griesgletscher in September 1977 was significantly higher than snow density at Ibergeregg in February/March due to greater maturity. Overall variations in water equivalent at Ibergeregg for different years and profiles depend much more on variations in snow depth than in snow density. These results are well known to snow specialists with many years experience but it is remarkable that a few student exercises can reproduce them.

LEHREN UND LERNEN IN EINEM PRAKTISCHEN KURS ÜBER SCHNEEHYDROLOGIE IN
DER SCHWEIZ, 1976–1979

ZUSAMMENFASSUNG

Für Studenten wurde von 1976 bis 1979 (Februar/März) ein praktischer Kurs in Schneehydrologie in der jahreszeitlichen Schneedecke (Ibergeregg, Alpenvorland) und im September 1977 auf dem Griesgletscher abgehalten. Einen halben Tag lang gruben die Studenten Schneeschächte, um die Eigenschaften des Schnees und die gemessene Schneedichte zu untersuchen. Sie maßen auch die Schneetiefe rund um die Schächte und das Wasseräquivalent an Pegeln entlang 1-km-Profilen. Die Datenanalyse und Diskussion mit den Studenten zielte auf den Vergleich der unterschiedlichen Messarten in verschiedenen Jahren und Profilen ab. Aufgrund der schlecht ausgewählten Lage der Schneeschächte war die Schneetiefe in den Schächten beträchtlich größer als die durchschnittliche Tiefe rund um die Schächte. Die Schneedichten aus horizontalen und vertikalen Proben zeigten keinen wesentlichen Unterschied in der durchschnittlichen Dichte, obwohl die Schwankungen zwischen ± 20 und $\pm 41 \text{ kg m}^{-3}$ lagen. Aufgrund der größeren Alterung der Schneedecke war die Schneedichte am Griesgletscher im September 1977 bedeutend höher als am Ibergeregg im Februar/März. Die gesamten Schwankungen im Wasseräquivalent am Ibergeregg (verschiedene Jahre und Profile) hängen sehr viel mehr von der unterschiedlichen Schneetiefe als von der Schneedichte ab. Erfahren Schneexperten wissen dies, aber es ist bemerkenswert, dass einige übungsweise Messungen von Studenten diese Ergebnisse bestätigen.

INTRODUCTION

Routine measurements of the characteristics of snow cover, including snow depth and density, are made as part of glacier mass balance studies (Østrem and Brugman, 1991). These measurements are made by a relatively small number of hardy people, who have usually been trained through a kind of apprenticeship under a more experienced operator. However, the increasing importance of snow and ice in many areas of environmental science means that elements of glaciology must be included in academic courses in geography, geology, remote sensing, geodesy, geophysics, hydrology, coastal engineering, meteorology and forestry. Few graduates of these courses will ever work in practical glaciology but they will all benefit by some insight into glaciological methods and ideas. For example, current concern about anthropogenic climate change has made many people aware of the link between glacier mass balance and sea level change, and reliable projections of sea level changes in the coming century must be based on a better understanding of glaciers. People who have never even been on a glacier are now writing papers about glaciers and their behaviour. There is therefore a need for glaciological education far beyond the needs of professional glaciologists.

The late Fritz Müller (1926–1980) was a university teacher and a tough field worker on glaciers. He definitely believed in the educational value of the snow shovel and the sampling tube. While teaching at McGill University, Montreal, Canada, in the late 1960's, Fritz Müller held an annual practical class in the snow (which I attended) and this was resurrected in the 1970's after Müller moved to the Swiss Federal Institute of Technology (ETH), Zürich. At the ETH, Professor Müller charged me with the practical details of running these classes and, despite the passage of nearly a quarter of a century, it is still worthwhile to share this experience with the wider community.

ORGANISATION AND PHILOSOPHY

The practical organisation of the field courses provided the limits within which the specific contents could be determined. For the purposes of the practical course, the scope of "snow hydrology" is what can be achieved in the time available. The contents did not have to be exhaustive but had to simply supplement classroom lectures on hydrology and glaciology given by Fritz Müller to diploma students at the ETH and the University of Zürich. The Swiss diploma corresponds roughly to the Anglo-American masters degree and the students are typically older and more mature than British undergraduates. As attendance was voluntary, not directly related to a specific lecture course, and not assessed, the field course was "free standing". It was also "self contained" in that all work was completed by the end of the field course.

From the beginning, the basic concept was for a 3-day field course, including travel time from Zürich to Ibergeregge in the Alpine foothills, where sufficient snow and suitable accommodation (beds and meals) were available. Friday morning and Sunday afternoon were used for travel and practical arrangements. The course itself was set up in half-day modules on micrometeorology (A. Ohmura, now Professor A. Ohmura, ETH, Zürich), surveying (H. Ito, now Dr H. Ito, National Institute of Polar Research, Tokyo) and snow hydrology (the present author). The students were divided into three groups so that they rotated between the three activities. Friday and Saturday evenings were devoted to data analysis and Sunday morning was a plenary session with "summary and feedback".

During the effective two days of the field course, each participant spent a half-day, (morning or an afternoon) on the snow hydrology exercises. These began with a short introduction into problems and techniques of snow hydrology (teacher centred) and then the group was divided into three smaller teams of 2–3 persons to carry out the practical exercises (student centred). Each participant was given a printed handout (in German) containing definition, descriptions of methods, practical information and references to further reading. [It is amusing to note that the handout only stated *der Zweck* of the course while modern British education must concern itself with *aims*, *objectives* and *outcomes*.] After the first year, the handout contained data summaries from previous years and students were asked to compare their results with the earlier ones.

The field courses at Ibergeregge were carried out in late-February or early March for each of the 4-years 1976 to 1979. Aside from the four Ibergeregge field courses, the International Glaciology Course conducted in Switzerland in September 1977 by the late Professor W. Hofmann (Kuhn, 1978) provided an opportunity to organise similar exercises in the accumulation area of Griesgletscher, Kanton Wallis, Switzerland. Although that glacier course was nominally held near the snout of Aletschgletscher, we actually found the accumulation area of Griesgletscher more accessible (by a combination of cable car, minibus and foot).

The demonstration of various field techniques (teacher centred) was an obvious start to all the exercises but even in the late 1970s, it was clearly necessary to provide a predominant amount of student activity. Snow depth and density could be measured within the half-day available and, as these measurements are both needed to determine the water equivalent of a seasonal snow cover, their importance for snow hydrology is self-evident. Many of the students had a strong background in maths and physics and were used to making their own measurements of well-known physical quantities. However, in the nature of snow hydrology, it is not possible to compare measurement results with the "right answers". The next best thing is to measure the same things in different ways, at different sites, and to compare the results with each other. Results from previous years give a further bonus when the current results can be compared with them. These comparisons naturally involved calculating simple descriptive statistics and testing hypotheses as part of the data analysis. We felt quite "high-tech" in providing three Hewlett-Packard HP35 pocket calculators for the data analysis sessions (involving a total of 20 to 30 students).

When planning the practical classes, I was inspired by Schytt (1962), who described the field programme on Storglaciären where snow depths are measured at hundreds of sites while snow density is only measured at a few sites. This implies a presumption that snow depth is somehow "more variable" than snow density, and therefore requires a larger measurement sample. This became one of the underlying hypotheses of the practical exercises.

CONTENTS OF THE EXERCISES

Each group was provided with a sharp-edged garden spade for cutting through icy snow layers and a large-bladed snow shovel for shovelling out loose snow. A snowprobe or avalanche probe (a sharp point with four 1-m sections) was used for measuring snow depths, and cylindrical sampling tubes (stainless steel) and spring balances were provided for measuring snow densities. Each student group (2–3 students) was asked to do the following:

- 1) Dig a snowpit through the seasonal snow cover to bare ground at a site close to the Ibergeregge hut. Identify the individual layers in the snow pack and then draw a vertical

- profile of grain size and shape, hardness, and free water content using the international snow classification system (UNESCO, 1970; Colbeck and others, undated).
- 2) In the snowpit, determine the water equivalent and bulk density of the snow cover by measuring densities of the individual snow layers by horizontal sampling with small sampling tubes (500 cm³).
 - 3) In the snowpit, determine the water equivalent and bulk density of the snow cover by taking successive vertical samples from the snow surface to the bare ground, using the large sampling tubes (up to 3,856 cm³), and compare results with those from (2).
 - 4) Dig a snowpit close to each of the 30 stakes, constituting three profiles of about 1 km in length in the altitude range 1400–1500 m a.s.l., and determine the total water equivalent by taking vertical snow samples. Due to pressure of time, each team can only cover 3 or 4 stakes but all 30 stakes are covered during the 1½ days of fieldwork.
 - 5) Using the snowprobe, measure the snow depth at 10 randomly chosen points within about 5 m of each stake, and compare the 10-point mean values with the snow depths in the snowpits.

The first exercise relates to the observation and description of the important characteristics of the snow cover (UNESCO, 1970). Exercises (2) and (3) relate to the determination of the water equivalent at a point by two different methods, and comparison of the results gives an idea of the accuracy to which snow density can be determined. The horizontal sampling method is typically used for snow engineering and avalanche studies while the vertical sampling method is sufficient for hydrological purposes (Arbeitsgruppe für operationelle Hydrologie, 1985). Both determinations are influenced by substantial measurement errors, especially associated with the volume of the snow sample, while the results of (2) will be also unreliable if the individual snow layers are not correctly identified.

Exercise (4) relates to the spatial variability of the water equivalent, snow depth and density at roughly 100 m intervals along a profile. Comparison of the 10-point mean snow depths from (5) with the snow depths in the snowpits in (4) illustrates the representivity, or otherwise, of single point measurements on a 10 m scale. The profiles in the four different years were established in roughly the same directions but the measurement sites were not permanently marked. This means that the 10 stakes of a profile sample the same general environment in each year but not the same specific stake locations.

After completing the exercises, and the data analysis, students were asked to reflect on the following questions:

- 6) How exact are the snow depths and water equivalents at single points?
- 7) How representative are single-point measurements for average conditions on the 100 m and 10 m scales?
- 8) How many depth and density measurements are needed to determine the water equivalent of an area?

These are still practical questions. For example, snow survey data from Switzerland are used for short-term forecasting of discharge in the River Rhine but Lang and others (1987) judge the field data inadequate.

As part of the International Glacier Course in September 1977 on Griesgletscher, participants could address most of these points in a modified form. For example, the snowpit in (1) to (3) was dug through the 1976/77 annual accumulation to a snow layer that could be identified as the 1976 summer surface instead of being dug to bare ground. The km profiles

of (4) were omitted because participants had already had to walk a considerable distance to the measurement site, and the 10-point mean in (5) refers to measurements around the same snowpit as (1) to (3). Participants could still reflect on (6) to (8) except for measurements on 100 m scale in (7).

RESULTS

The participants in the Ibergeregg field courses were enthusiastic and motivated. This was partly the result of self-selection because the course was not compulsory but also because most students had already had considerable experience of snow through skiing or basic training in the Swiss army. The data analysis and discussion sessions were stimulating because students could speak from their own fresh experience.

One practical matter emerged about the need for field books and data recording forms. Where I had provided these, I was able to recover and archive data almost completely, e.g. the results of (4) and (5), but any data written down on loose scraps of paper rapidly became inaccessible, e.g. results of (1) to (3) for the first two years at Ibergeregg. This means that I now have very little record of the snowpit profiles that were drawn. However, it would be safe to say that the four years of measurement at Ibergeregg, and one year on Griesgletscher, showed no traces of snow with dry metamorphism, or re-crystallisation features like depth hoar. We sometimes saw remnants of new snow but most features reflected the effects of repeated melting and refreezing. This was inevitable for both sites.

During the four years 1976–79, snowpit measurements were made in three 1-km profiles of ten stakes. This implies 120 snowpits ($4 \times 3 \times 10$) but results from one snowpit (in 1977) are unaccountably missing. The following data are therefore available for 119 snowpits: snow depth in the snowpit (d_1), the average of 10 snow depth measurements around the snowpit (d_{10}), the bulk density of snow in the snowpit (ρ), the water equivalent calculated (w_1) from density and snow depth d_1 , and the water equivalent (w_{10}) calculated from density and snow depth d_{10} . If anyone wishes to use these data for teaching purposes, they are available on request from the author in EXCEL format.

SNOW DEPTH

Snow depths determined by two different methods are shown in Figure 1. The snow depths around stake are averages of 10 snowdepth measurements with a snowprobe within a roughly 5 m circle around each snowpit. Although the two kinds of snow depth estimate are strongly correlated ($r = 0.90$, significant at less than 5 percent probability), the single-point values are higher than the 10-point values (Table 1). Application of Student's t-test confirms that the difference is statistically significant at less than 5 percent probability.

Table 1: Snow depth, snow density and water equivalent measured at Ibergeregg 1976–1979. Data are mean \pm standard deviation for N snowpits

| Variable | Units | N | Single-point | 10-point | Difference |
|------------------|--------------------|-----|-----------------|-----------------|-------------------|
| Snow depth | m | 119 | 1.11 ± 0.37 | 1.05 ± 0.34 | $+ 0.06 \pm 0.16$ |
| Snow density | kg m^{-3} | 119 | 367 ± 43 | N/A | N/A |
| Water equivalent | kg m^{-2} | 119 | 407 ± 145 | 385 ± 132 | $+ 22 \pm 64$ |

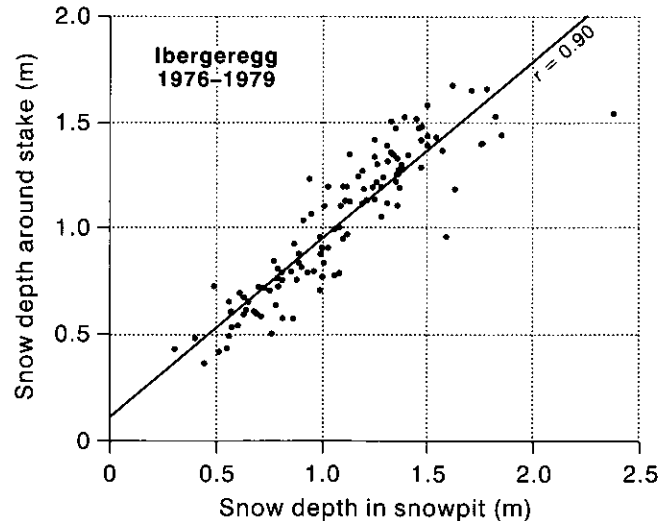


Fig. 1: Snow depth around stake (10-point means) compared with snow depth in snowpit (single points), Ibergereg, 1976-1979.

One possible reason for single-point snow depth being greater than 10-point values emerged from discussion with participants. This is the suggestion that one naturally (but sub-consciously) avoids slopes and depressions when choosing the site of a snowpit. This leads to snowpits being biased towards level sites, i.e. topographic bias. However, when walking around a snowpit, trying to sample snowdepth at regular intervals, it is more difficult to sub-consciously reject slopes and depressions, and the 10-point results are therefore more representative of the real topography. However, some students argued that an opposite bias ought to occur. This is because 10-point snow depths are measured with a snowprobe and most people will tend to push the probe right through the snowcover into the soft ground underneath, i.e. snowprobe overshoot. By comparison, the snow depth measured in the snowpit should be more reliable because one can actually see the ground surface. Frequent traces of mud on the tip of the snowprobe shows that overshoot occurs but the effect is probably to only overestimate snow depths by 0.01-0.02 m. Presumably the average +0.06 m discrepancy between the two snow depths is the net result of a much larger topographic bias partly offset by the smaller snowprobe overshoot.

SNOW DENSITY

Snow densities determined by the horizontal and vertical sampling methods are shown in Figure 2. There is one large anomaly in the Griesgletscher data where the horizontal sampling value is much larger than the vertical sampling value. This was noticed the evening after data collection and the group concerned admitted having deviated from the written instructions for the measurements. [Different spring balances were provided for weighing the smaller horizontal and larger vertical samples but one group, on their own initiative, used the same spring balance for all the measurements. As this was the balance intended for vertical sampling that measurement was correct, but the balance was insufficiently loaded to

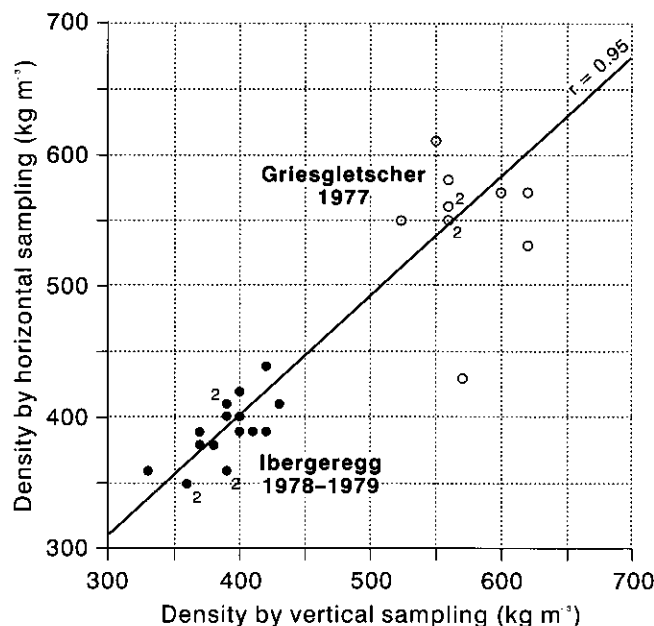


Fig. 2: Snow densities determined by horizontal and vertical sampling, Ibergeregg 1978–1979 and Griesgletscher 1977. Regression line excludes 1 anomalous point for Griesgletscher.

correctly weigh the lighter horizontal samples, hence the gross underestimation of their density. This example shows the potential pitfall of being too student-centred in a subject requiring technical knowledge but it did lead to a fruitful discussion in the evening.] Aside from this error, there is good average agreement between the two techniques (Table 2).

Table 2: Snow density measured by horizontal and vertical sampling techniques in two different environments (excluding 1 anomalous point for Griesgletscher). Data are mean \pm standard deviation, and units are kg m^{-3} .

| Environment | N | Horizontal | Vertical | Difference |
|----------------|----|--------------|--------------|-------------|
| Ibergeregg | 18 | 388 ± 25 | 389 ± 25 | -1 ± 20 |
| Griesgletscher | 10 | 563 ± 22 | 572 ± 30 | -9 ± 41 |
| Combined | 28 | 451 ± 88 | 454 ± 93 | -3 ± 29 |

A student's t-test (Kreyszig, 1970), shows that the differences between the techniques are not statistically significant at the 5 percent probability level, although differences between the techniques at single sites already affect the second digit in the density values. This provided material for interesting discussions with participants on the difference between "accuracy" and "precision" with geodesy and geophysics students tending to read instruments to a greater precision than geography or geology students. Although there is no firm basis for claiming that one method is "better" than the other, most participants thought that the horizontal method underestimates densities in comparison to the vertical method because any ice layers would not be sampled by the horizontal method. However, some

thought that the vertical method underestimates bulk density because of the loss of measurement horizon, i.e. the snow column being weighed is actually shorter than one thinks. A snow sample with overestimated volume will obviously have an erroneously small density.

The snow density is clearly greater at Griesgletscher than Ibergereg (Fig. 2 and Table 2). This expresses the greater maturity of the snowpack by September when the Griesgletscher data were collected. In fact, the Griesgletscher snow shows the classical characteristics of firn with density close to the value of 550 kg m^{-3} quoted in textbooks (Paterson, 1994, p. 17).

WATER EQUIVALENT

The water equivalent (w_i) of a snowcover at site i is calculated from snow depth (d_i) and density (ρ_i) at the same point:

$$w_i = d_i \times \rho_i \quad (1)$$

However, the *variability* of the water equivalent will be determined by whichever of the dependent variables d and ρ is the more variable. The standard deviation of snow depth for the 119 sites is ± 32 percent of the corresponding mean value (values in Table 1 referring to 10-point values). By comparison, the standard deviation of snow density is only ± 12 percent. This suggests that variations in snow depth are more responsible for the variations in water equivalent (± 34 percent of the mean) than are density variations. This is confirmed by the high correlation ($r=0.93$ & $N=119$) between water equivalent and snow depth (Fig. 3), and the low correlation ($r=0.23$ & $N=119$) between water equivalent and snow density (Fig. 4). The correlation between depth and density is also very low ($r = -0.14$ & $N=119$) in the Ibergereg case although this may not be the case on a glacier, e.g. see Jansson (1999).

In both Figures 3 and 4 "water equivalent" refers to the water equivalent calculated at each of the 119 sites using the density determined for that snowpit and the mean snow depth around the stake. As these estimates use the maximum amount of data, they are assumed the "best" estimates available. However, the high correlation in Figure 3 suggests that a reasonably accurate estimate of water equivalent can be made using the measured snow depth for each site and a mean density measured at a much smaller number of sites. This point is illustrated by the standard errors of mean snow depth and density in Table 3. [Standard error is the standard deviation of the sample divided by the square root of the sample size, $N=119$ in the present case]. The standard error of snow depth is about 3.2 percent of the mean for $N=100$ but snow density has the same standard error for a sample size of only 13. Again, the standard error of snow depth is about 4.6 percent for $N=50$ while snow density has the same standard error for only 7 points. One therefore needs about seven times as many snow depth measurements as snow density measurements to achieve equivalent sampling errors for the two quantities. This result is particularly attractive because density is more difficult and time-consuming, and therefore more expensive, to measure than the depth (Goodison and others, 1981). Standard Swiss practice is based on a similar conclusion (Arbeitsgruppe für operationelle Hydrologie, 1985, p. 29).

There are substantial differences in water equivalent at Ibergereg for the four years 1976–1979, and smaller differences between the different profiles (Fig. 5). This can be confirmed by a two-way analysis of variance but it is clear to the naked eye. For three of the

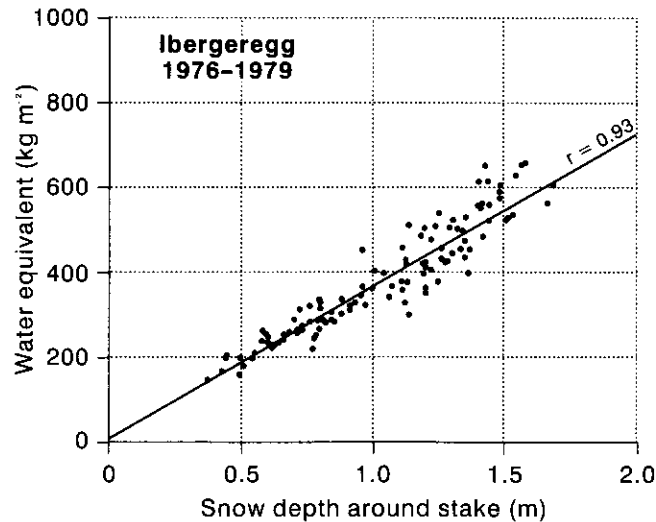


Fig. 3: Water equivalent versus snow depth around stake (10-point mean), Ibergeregg, 1976–1979.

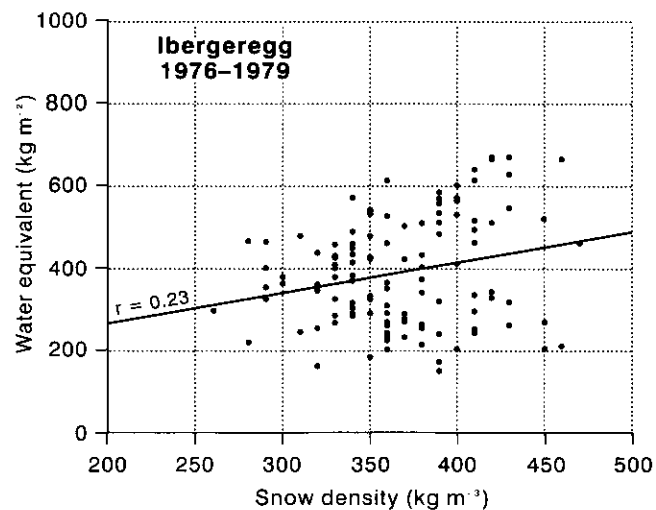


Fig. 4: Water equivalent versus snow density, Ibergeregg, 1976–1979.

four years, profile 2 gives the lowest water equivalent. Similar plots of snow density and snow depth (not shown here) confirm that year-to-year variations in water equivalent are mainly accounted for by variations in snow depth.

The variations in Figure 5 refer to late February or early March when the field courses were held. Rohrer and Lang (1989) describe longer-term variations, i.e. 1975–1989, for water equivalent on 1 April and 1 May. According to their graphs, the 1 April water equivalent north of the Alps was exceptionally low for 1976. Water equivalent for 1977 and 1979

Table 3: Statistics of snow depth (standard deviation, mean, coefficient of variation, and standard error) and snow density

| | Snow depth (m) | Snow density (kg m ⁻³) |
|--------------------------|-------------------|---------------------------------------|
| Standard deviation | 0.34 | 43 |
| Mean | 1.05 | 367 |
| Coefficient of variation | 0.32 | 0.12 |

| Sample size | Standard error (% of mean) | Standard error (% of mean) |
|-------------|-------------------------------|-------------------------------|
| 1000 | 0.010 | 0.004 |
| 500 | 0.014 | 0.005 |
| 100 | 0.032 | 0.012 |
| 50 | 0.046 | 0.017 |
| 10 | 0.102 | 0.037 |
| 5 | 0.145 | 0.052 |

were moderately lower than average, and only 1978 was higher than the average. The 1 May water equivalent north of the Alps was also exceptionally low for 1976, while it was slightly above average for the other three years. These variations bear little resemblance to those in Figure 5. The one or two months difference in measurement time is probably an important factor here.

DISCUSSION

The numerical results of the practical course and the conclusions that emerged from the discussion sessions may seem trite to snow specialists. However, in only a half-day field experience, supplemented by 1–2 hours evening work, participants were able to *learn* things about water equivalent for themselves that would have been difficult to *teach*. In particular, the meaning of statistical concepts like standard deviation and confidence interval are clearer to students who had just recently generated the data for themselves.

The practical classes ceased after only four years, and I often speculate about how they might have been developed further. The link between the fieldwork and the application of simple statistical techniques, e.g. hypothesis testing with the t-test, was already quite well established using pocket calculators. However, various advances in technology would have been incorporated into the practical work when portable PC's became available with powerful statistics packages, e.g. more sophisticated multivariate models.

Establishing the stakes at fixed locations from year to year would have introduced an extra dimension into the multivariate data analysis, with an ever-increasing sample size. The scope of the field course would have expanded to include fixing the locations of the permanent stakes by global positioning system (GPS). A digital elevation model (DEM) of the area might have been constructed and relations between snow depth and topography could have been explored in greater detail. Large-scale variations in snowcover could have been studied by establishing a library of suitable satellite images.

The field course might even have reflected the shift in emphasis in mainstream hydrology from water quantity to water quality, and included studies of snow water chemistry.

Measurements of snow depths in one- or two-dimensional grid can be made so quickly

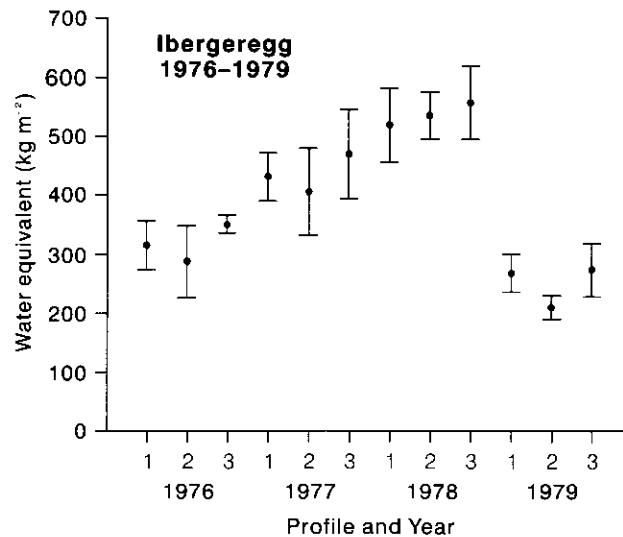


Fig. 5: Water equivalent for different profiles and years. Error bars refer to the 95 percent confidence interval around the mean.

that they could even be used for courses that have little directly to do with snow. For examples, exercises in geostatistics or geographical information systems (GIS) could be based on the results of snowprobing. The data collection is simple enough for students to overview the data quality and, if the data analysis were made quickly enough, a team could be sent out again to test predictions, e.g. snow depth in a part of the field that was deliberately excluded from the first data collection.

CONCLUSIONS

With a half-day's fieldwork, supplemented by evening work, participants learned things that would have been difficult to teach. They could also better understand the data analysis because they had just collected the data for themselves. The specific conclusions of the practical exercises include the following:

Snow depth in snowpits is significantly higher than snow depth measured by snowprobe around snowpits. This is probably because the snowpits are biased to level sites i.e. topographic bias, but this may be partly offset by snowprobe overshoot.

There is no statistically significant difference between snow densities measured by horizontal and vertical sampling although discrepancies amount to ± 20 to ± 41 kg m⁻³.

Snow density at Griesgletscher in September is significantly higher than snow density at Ibergeregg in February/March because of the greater maturity of the snowpack.

Although water equivalent of a snow cover depends upon both snow depth and density, variations in water equivalent are mainly due to variations in snow depth.

The relative importance of snow depth and density variations is such that about seven times as many depth measurements as density measurements are needed to have equivalent effects on uncertainties in water equivalent. This is a desirable result as density is more difficult and time-consuming to measure than the depth.

Water equivalent at Ibergeregg in February/March varied substantially between the four years 1976–1979, mainly due to variations in snow depth.

ACKNOWLEDGEMENTS

The Ibergeregg field courses 1976–1979 were lead by the late Fritz Müller (1926–1980) and the data of this study were collected by about 100 course participants spread over four years. Karl Schrott, Geographical Institute, Swiss Federal Institute of Technology (ETH), and Paul Gnos, then at the Department of Glaciology and Hydrology (VAW-ETH), provided field equipment and practical help for the field exercises. Jakob Weiss, Geographical Institute, Swiss Federal Institute of Technology (ETH), and some senior students helped to demonstrate techniques.

REFERENCES

- Arbeitsgruppe für operationelle Hydrologie, 1985: *Die Schneedecke in der Schweiz aus hydrologischer Perspektive. Bestandsaufnahme und Empfehlungen der Arbeitsgruppe „Schneedecke und Hydrologie“*. Landeshydrologie. Bern
- Colbeck, S., Akitaya, E., Armstrong, R., Gubler, H., Lafeuille, J., Lied, K., McClung, D., Morris, E., undated: *The international classification for seasonal snow on the ground*. International Commission on Snow and Ice. Bibliographic information not given.
- Goodison, B. E., Ferguson, H. L., McKay, G. A., 1981: Measurements and data analysis. In Gray, D. M. and D. H. Male (eds) *Handbook of snow: principles, processes, management & use*. Toronto. Pergamon Press.
- Jansson, P., 1999: Effects of uncertainties in measured variables on the calculated mass balance of Storglaciären. *Geografiska Annaler* 81A(4), 633–642.
- Kreyszig, E., 1970: *Introductory mathematical statistics*. New York, John Wiley and Sons.
- Kuhn, M., 1978: Der 19. Gletscherkurs am großen Aletschgletscher, 10.–17. September 1977. *Zeitschrift für Gletscherkunde und Glazialgeologie* 14(2), 227–229.
- Lang, H., Jensen, H., Grebner, D., 1987: Short-range runoff forecasting for the River Rhine at Rheinfelden: experiences and present problems. *Hydrological Sciences – Journal des Sciences Hydrologiques* 32 (3), 385–397.
- Østrem, G., Brugman, M., 1991: *Glacier mass balance measurements: a manual for field and office work*. National Hydrology Research Institute, Saskatoon, Canada, and the Norwegian Water Resources and Electricity Board, Oslo, Norway.
- Paterson, W. S. B., 1994: *The physics of glaciers*. (3rd Edition). Oxford: Pergamon.
- Rohrer, M., Lang, H., 1989: Wie außergewöhnlich war der Winter 1988/89? *Wasser, Energie, Luft – Eau, Énergie, Air* 81(7/8), 169–172.
- Schytt, V., 1962: Mass balance studies in Kebnekasje. *Journal of Glaciology* 4(33), 281–289.
- UNESCO, 1970: *Seasonal snow cover: a guide for measurements, compilation and assemblage of data*. United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris.

Manuscript received 9 August 2000

Author's address: R. J. Braithwaite
School of Geography
University of Manchester
Manchester M13 9PL, England