Hydrology in Mountainous Regions. I - Hydrological Measurements; the Water Cycle (Proceedings of two Lausanne Symposia, August 1990). IAHS Publ. no. 193, 1990.

Estimation of Alpine glacier water resources and their change since the 1870s

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ABSTRACT An empirical formula relating volume of an Alpine glacier to the surface area is improved based on the data measured by radio-echo sounding and seismic method. The formula is used for calculating the present volume of the Alpine glaciers based on the surface-area data registered in the World Glacier Monitoring Service. The past volumes at several stages are estimated from the surface area and its change.

The ice-covered area of the Alpine glaciers was 4368±54 km^2 in the 1870s, 3541±33 km^2 in the 1930s, and 2909 km^2 in the 1970s. For the period 1870s-1970s, the volume of Alpine glaciers decreased by 57.4±20.4 km^3 with the volume in the 1970s being 140±10 km^3. The mean rate of changes over this period is about -15 km^2/a for the ice-covered area, -0.574 km^3/a for the volume and -0.163 m/a for the mean thickness.

The mass-turnover time of an Alpine glacier, which is important in investigating the water cycle of a basin with glaciers, is estimated to be in the order of 10^1-10^2a.

INTRODUCTION

It is of both scientific and practical importance to know the present amount of and historical changes in the water stored in the Alpine glaciers. The significant decrease in the volume of small glaciers and ice caps may contribute to sea level rise (Meier, 1984). In addition, the Alpine glaciers are of special significance as water resources. As an example, almost 64% of the electricity consumed in Switzerland is from the hydro-power plants and 24% is produced through the reservoirs which collect glacier meltwater (Müller et al., 1976).

The present ice-covered area of the Alpine glaciers is rather accurately known through the glacier inventory (Haeberli et al., 1989). The volume given through the glacier inventory is 67.4 km^3 for the Swiss glaciers (Müller et al., 1976) and 21 km^3 for the Austrian glaciers according to Patzelt (1980) whereby various estimation methods were used. A literature survey suggests that the present ice volume and the changes in the ice-covered area is known only for local regions and not for the whole Alps (Vivian, 1975; Müller et al., 1976; Kasser, 1981; Gross, 1987). In comparison with changes in ice-covered area, the changes in thickness and volume are much poorly understood.

In this work, the volume of the Alpine glaciers in the 1970s are estimated according to an improved empirical volume-area relationship and the data base of the Alpine glacier inventory registered in the World Glacier Monitoring Service. The changes in area and volume of the Alpine glaciers for the period 1870s-1970s are examined. Finally, the mass turnover time of an Alpine glacier is briefly discussed.

THE EMPIRICAL VOLUME-AREA RELATIONSHIP

The volume V of a glacier is well related with its surface area S and a power relationship is commonly applied:

$$V = c_0 S^{c_1} \tag{1}$$

with c_0 and c_1 being the empirical constants which are often deduced from the measured V and S. The common method for finding V of a glacier is to measure its thickness after the grid points or along profiles. A chart of the thickness-isoline is compiled and V can then be calculated. The accuracy of V is therefore strongly influenced by that of thickness soundings. The volume estimation of the Swiss glaciers by Müller et al. (1976) is based on Brückl's (1970) thickness-area relationship:

$$\langle h \rangle = 5.2 + 15.4\, S^{0.5} \tag{2}$$

where $\langle h \rangle$ [m] denotes the mean thickness over the entire glacier and S [km^2] is the surface area. Equation 2 was then the best available formula and used for the Swiss glacier inventory.

Equation 2 was based on the depth measurements by seismic soundings for 16 Alpine glaciers. Recently, a number of mountain glaciers have been measured through radio-echo soundings (Driedger & Kennard, 1986; Zhuravlev, 1988). The experiments on Swiss glaciers show that rather reliable results can be obtained through radio-echo soundings (Wächter, 1981; Haeberli et al, 1983). As the measured V data of more glaciers become available, it is possible to improve equation 2. From the data of 63 mountain glaciers (Table 1), it is found that:

$$V = 28.5\, S^{1.357} \tag{3}$$

with the squared correlation coefficient $r^2 = 0.96$ (Fig. 1). The unit of V is in 10^6 m^3 and that of S is 10^6 m^2. The standard deviation of the residuals s_e of equation 3 increases with S. s_e [10^6 m^3] is 0.43 for S [10^6 m^2] ≤ 0.5, 12.9 for $0.5 < S \leq 1.0$, 62 for $1.0 < S \leq 5.0$, 115 for $5.0 < S \leq 10.0$ and 303 for $10 < S \leq 20.0$. From equation 3, the mean thickness $\langle h \rangle$ is

$$\langle h \rangle = 28.5\, S^{0.357} \tag{4}$$

and the change in the volume ΔV of a mountain glacier can be approximated from the change in the surface area ΔS:

$$\Delta V = 38.716\, S^{0.357}\, \Delta S. \tag{5}$$

DISCUSSION ON THE VOLUME-AREA RELATIONSHIP

Equation 3 just concerns the mountain glaciers (except for ice-caps). It is deduced from the measured data of different accuracy and from the glaciers in different regions. The selected glaciers include 15 from the Alps (Brückl, 1970), 23 from the Cascade Ranges, 2 from the Rocky Mts., 1 from Wind River Range, 1 from Sierra Nevada, 1 from Mt. Shasta, 2 from the Kebnekaise Massif (Driedger & Kennard, 1986) and 17 from Svalbard (Zhuravlev, 1988). The $\langle h \rangle_m$ or V of some Svalbard glaciers may be underestimated (Dowdeswell & Drewry, 1984). It is therefore necessary to give some discussions on equation 3 before it is used for the Alpine glaciers.

Firstly, the magnitudes of the coefficients c_0 and c_1 in equation 1 remain within a certain range (Table 2). Except for the V-S relationship for 17 Svalbard glaciers, c_0 is between 17-30 and c_1 is between 1.15-1.52 whereby the difference is due to the fact that various types of glaciers are involved and due to accuracy of V determinations. Furthermore, two parameters which are physically related to the mean thickness are not considered in the V-S relationship: the surface slope and the basal shear stress (Paterson, 1970). The main difficulty in involving them is due to the data availability.

TABLE 1 The measured volume V [$10^6 m^3$] and area S [km^2] used in this work. $<h>$ [m]: the mean thickness. $<h>_m = V/S$. $<h>_1$: this work (eq. 3). $<h>_2$: by eq. 2 after Müller et al. (1976). Data sources: 1 Brückl (1970), 2 Driedger & Kennard (1986), 3 Zhuravlev (1988), 4 cited from 2, 5 Kappenberger (1976), and 6 Wächter (1981) and Haeberli et al. (1983). * Not considered in eq. 3. **V is underestimated (Dowdeswell & Drewry, 1984)

Name	ϕ [°N]	λ [°]	S	V	$<h>_m$	$<h>_1$	$<h>_2$	Sources
Athabasca*	51 40	116 50 W	3.8	574	150	46	35	4
Brandner	47 04	9 42 E	2.08	29.12	14	37	27	1
Carbon	46 56	121 47 W	7.92	710	90	60	49	2
Cascade S.	48 22	121 03 W	3.3	196	59	44	33	4
Coalman	-	-	0.08	1	14	12	15	2
Coe	-	-	1.2	53	43	30	22	2
Collier	-	-	1.1	21	19	30	21	2
Diller	-	-	0.66	13	20	25	18	2
Dinwoody	43 10	109 40 W	1.5	80	55	33	24	4
Eliot	-	-	1.7	91	54	34	25	2
Emmons	46 52	121 41 W	11.17	672	60	68	57	2
Findelen	46 01	7 51 E	19.09	1489.02	78	82	72	1
Gefrorenewand*	47 04	11 40 E	4.59	91.8	20	49	38	1
Gepatsch	10 46	46 51 E	17.69	1328	71	80	70	1
Gosau Gr.	47 29	13 36 E	1.48	42.92	29	33	24	1
Grinnell	48 50	113 50 W	1	62	64	29	21	4
Gurgler	46 48	10 59 E	11.14	401.04	36	67	57	1
Guslar Gr.	46 51	10 49 E	1.76	49.28	28	35	26	1
Hallstaetter	47 29	13 37 E	3.3	108.9	33	44	33	1
Hayden	-	-	0.72	19	26	25	18	2
Hintereis	46 48	10 46 E	9.47	473.5	50	64	53	1
Isfalls	67 55	18 34 E	1.4	92	72	32	23	4
Kesselwand	46 50	10 48 E	4.24	284.08	67	48	37	1
Ladd	-	-	0.9	24	33	27	27	2
Langille	-	-	0.4	8	20	21	5	2
Lost Creek	-	-	0.54	14	21	23	17	2
Maclure	37 40	119 10 W	0.2	4	17	16	5	4
Newton-Clark	-	-	2	39	20	37	27	2
Nisqually	46 48	121 44 W	4.6	220	48	49	38	2
Palmer	-	-	0.13	2	16	14	5	2
Pasterzen	47 06	12 41 E	19.78	1246.14	63	83	74	1
Prouty	-	-	1	16	17	29	21	1
Rabots	67 54	18 33 E	4.1	346	84	47	36	4
Reid	-	-	0.75	18	24	26	19	2
Russell	-	-	3.3	86	26	44	33	2
Sandy	-	-	1.2	25	21	30	22	2
Schladminger	47 28	13 38 E	0.81	7.29	9	26	19	1
Schiedinger	47 12	12 41 E	1.81	45.25	25	35	26	1
Storgl.	67 54	18 34 E	3.12	306	99	43	32	4
Sulztal	47 00	11 05 E	4.14	198.72	48	47	37	1
Tahoma N.-L.	46 50	121 49 W	8.63	457	52	62	50	2
Vernagt	46 53	10 49 E	9.56	583.16	61	64	53	1
White River	-	-	0.54	8.9	16	23	17	2
Whitney	41 25	122 13 W	1.38	26	20	32	23	4
Wilson	-	-	1.4	54	38	32	23	2
Winthrop	-	-	9.2	525	57	63	52	2
Zigzag	-	-	0.78	17	22	26	19	2
Zmutt	46 00	7 38 E	16.98	1341.42	79	78	69	1
Aldegonda	-	-	10.3	710	69	66	55	3
Antonia	-	-	32	4000	125	98	92	3
Bertill	-	-	6	440	73	54	43	3
Boger	-	-	4.5	300	67	49	38	3
Bruegger Bost	-	-	13.3	760	57	72	61	3
Bruegger Zap.	-	-	5.6	240	43	53	42	3
Vöring	-	-	2.1	130	62	37	28	3
Dalfonna	-	-	9.8	860	88	64	53	3
Lein	-	-	4.1	310	76	47	36	3
Loven Srednii	-	-	5.8	370	64	53	42	3
Meryal	-	-	6.4	470	73	55	44	3
Penk**	-	-	83	8850	107	141	146	3
Revtan	-	-	5.9	290	49	54	43	3
Suess	-	-	9	540	60	62	51	3
Finsterwalder**	-	-	38	2800	74	105	100	3
Gess	-	-	7.2	460	64	58	47	3
Erdman	-	-	11.2	1410	126	68	57	3
Laika*	75 55	79 15 W	4.28	223	52	48	37	5
Rhône*	46 37	8 24 E	17.38	1773	102	79	69	6
$\Sigma\|<h>_c - <h>_m\|/N$						14.6	16.9	
$\Sigma(<h>_c - <h>_m)/N$						-2.7	-12.1	

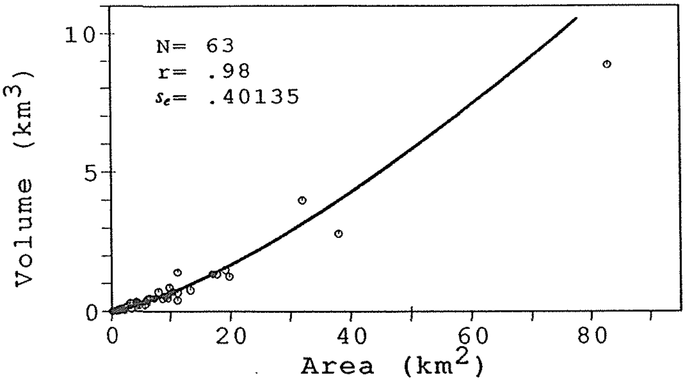

FIG.1 Relationship between the volume [km^3] and the surface area [km^2] of a mountain glacier. Based on the data from 63 glaciers in Table 1 (Brückl, 1970; Driedger and Kennard, 1986; Zhuravlev, 1988). r: the correlation coefficient. s_e: the standard deviation of the residuals.

Secondly, the accuracy of different V-S relationships can be evaluated by comparing the residual for the calculation of the mean thickness $e = \langle h\rangle_c - \langle h\rangle_m$. It can be shown that the residual is $e = -4.7 + 0.856\, S^{0.357}$ [m] for equation 4 of this work and $e = -19 - 0.554\, S^{0.5}$ for equation 2 (Brückl, 1970). It follows that equation 4 does give better results than the $\langle h\rangle$-S relationship applied in the Swiss glacier inventory by Müller et al. (1976).

Thirdly, the measured change in the mean thickness $\langle \Delta h\rangle$ or volume ΔV of a glacier, which is revealed by comparing the large scale topographic maps over relatively long period, are compared with the values calculated from equation 5 based on the known area of the glacier and the measured area change ΔS. From the data of 26 observations for Alpine glaciers (Finsterwalder,1953; Finsterwalder & Rentsch, 1973; Long & Patzelt, 1971; Chen & Funk, submitted), it is found that the standard deviation of the residuals of the linear relationship between the measured and the calculated values is 33x10^{6}m^3 for ΔV and 3.6 m for $\langle \Delta h\rangle$. The calculated and measured values agree fairly well, especially when the considered period is longer.

TABLE 2 Comparison of the values of coefficients c_0 and c_1 of equation 1. The coefficients for No. 2-9 are recalculated. N: number of the glaciers; r^2: the squared correlation coefficient; s_e [10^{6}m^3]: the standard deviation of the residuals; S: the area range; Method: Sei.-seismic soundings, Rec.-reconstructed from geomorhpological evidence, Rad. - radio-echo sounding, Mix.-seismic or radio-echo sounding, and Est.: estimated. Data source: 1 Erasov (1968) and cited from 6; 2 Brückl (1970); 3 Maisch (1981); 4 & 5 Driedger and Kennard (1986); 6 from 2 & 4; 7 Shi et al. (1981); 8 Zhuravlev (1988); 9 from 2, 4 and 8.

No	*N*	c_0	c_1	r^2	s_e	S [km^2]	Method	Mountain glaciers in	Data source
1	-	27.	1.5	-	-		-	Central Asia	1
2	16	16.133	1.520±0.092	0.95	110.9	0.9 -19.3	Sei.	Alps	2
3	63	24.626	1.391±0.033	0.97	35.3	0.4 - 7.5	Rec.	Graubünden, Alps	3
4	32	30.834	1.405±0.071	0.93	105.0	0.1 -11.0	Mix.	Cascade & other areas	4
5	15	21.346	1.145±0.041	0.98	3.3	0.08 - 3.3	Rad.	Cascade, small glaciers	5
6	49	27.551	1.358±0.045	0.95	166.5	0.08 -19.3	Mix.	Alps, Cascade and other areas	6
7	7	36.056	1.406±0.094	1.00	9.4	0.05 -7.02	Est.	Qilian Mountains, China	7
8	17	47.995	1.186±0.070	0.95	374.0	2.1 - 83.	Rad.	Mountain glaciers in Svalbard	8
9	63	28.524	1.357±0.037	0.96	401.4	0.08 - 83.	Mix.	Alps, Cascade and Svalbard etc.	9

ESTIMATION OF THE AREA CHANGE

The measured areas of 324 Swiss glaciers are selected and compared for the period of 1870s-1930s-1970s whereby the data are from Jegerlehner (1902), Rindlisbacher (1954) and Müller et al. (1976). It shows that the area of an Alpine glacier at different times is related with each other in the following manner for 218 glaciers larger than 0.5 km^2:

$$S(1870s) = 0.219 + 1.175\, S(1970s) \qquad (r^2 = 0.98\ \&\ s_e = 0.593) \qquad (6a)$$

$$S(1930s) = 0.100 + 1.103\, S(1970s) \qquad (r^2 = 0.99\ \&\ s_e = 0.398) \qquad (6b)$$

and in the forms below for 106 glaciers smaller or equal to 0.5 km^2:

$$S(1870s) = 1.024\, S(1970s)^{0.589} \qquad (r^2 = 0.61\ \&\ s_e = 0.305) \qquad (6c)$$

$$S(1930s) = 1.006\, S(1970s)^{0.800} \qquad (r^2 = 0.93\ \&\ s_e = 0.181) \qquad (6d)$$

with the decade in the bracket being the reference time.

A rough estimation of the change in the Alpine ice-covered area since the 1870s can be made under the following assumptions:
(1) The area of Alpine glaciers has not changed much after the inventory time (1970s). This seems to be reasonable (Wood, 1988);
(2) Equations 6 a-d are representative of the Alpine glaciers; and
(3) No glaciers have disappeared since the 1870s. This is not the case (Gross, 1987), but there is not an easy way to estimate.

The changes in the ice-covered area in the Alps are estimated by using equations 6 a-d for single glaciers registered in the data base of the WGMS, that is, using equations 6a and 6b for glaciers with $S > 0.5$ km^2 and equations 6c and 6d for glaciers with $S \leq 0.5$ km^2. The results are summarized in Table 3 for three stages: the 1870s, 1930s and 1970s.

The calculated Swiss ice-covered area is 1580±21 km^2 in the 1930s and 1848±38 km^2 in the 1870s which agrees well with the measured values given by Rindlisbacher (1954). According to Gross (1987), the measured ice-covered area in Austria in 1870/1873 is 995 km^2 which is based on Richter's (1888) work plus the small glaciers not considered by Richter. The area in 1920 calculated by Gross (1987) is 808 km^2 and the method for his calculation was not declared. The ice-covered area in the 1930s can thus be interpolated as 727 km^2 with a mean rate of -5.4 km^2/a for the period 1920-1969. These values are considerably larger than those estimated from equations 6 a-d, which are 782±27 km^2 in the 1870s and 652±15 km^2 in the 1930s. In fact, Richter apparently overestimated the glacier area since the rock area above the snow line was partly counted as glacier area. Moreover, the disappeared glaciers can not be considered in the present work which make a significant portion (6.4%). It may also suggests that the area loss of glaciers is much larger in the eastern Alps than in the Swiss Alps.

TABLE 3 Ice-covered area [km^2] for the period 1870s-1930s-1970s in the Alps. Data sources: 1 Alpine glacier inventory (Haeberli et al., 1989); 2 Rindlisbacher (1954), 3 Müller et al. (1976), 4 Gross (1987); 5 This work; and 6 Estimated from Gross (1987).

Reference period	France	Switzerland	Austria & Germany	Italy	Alps
1870s	640±25 (5)	1818 (2)	995 (4)	915±29 (5)	4368±54
1930s	516±18 (5)	1556 (2)	727 (6)	742±15 (5)	3541±33
1970s	417 (1)	1342 (3)	543 (1)	607 (1)	2909

ESTIMATION OF THE VOLUME AND ITS CHANGE

Equation 3 is applied for the single glaciers registered in the glacier-inventory data base of the World Glacier Monitoring Service to calculate the present ice-volume. For finding the volume change during the 1870s-1970s, equations 6a and 6c are used to estimate the area change ΔS and then the volume change is approximated by using equation 5. The results for the entire Alps are presented in Table 4. The uncertainty intervals are determined at the confidence level of 95%.

The results given in Table 4 are considered to be a rough estimation. However, it covers the entire Alps and it has improved the result of previous studies. Through the inventory, Müller et al. (1976) showed that the ice volume of the Swiss glaciers in 1973 is 67.4 km^3, which is obtained by applying equation 2 for the glaciers with $0.5<S<23$ km^2. A constant of $<h> = 5$ m was assumed for those with $S<0.5$ km^2 and individual estimation was made for those with $S>23$ km^2. It is clear that equation 2 underestimate the mean thickness of a glacier in most cases (Table 1). The present work shows that the total volume of Austrian glaciers is 22 km^3. This can be compared with the 21 km^3 which is given by Patzelt (1980) through glacier inventory and which is obtained by assuming a mean thickness of 40 m for all the Austrian glaciers.

The data in Table 3 suggests that the ice-covered area of the Alpine glaciers has decreased by 1459±54 km^2 or 33% for the period 1870s-1970s. The area loss during the 1870s-1930s (19%) is slightly larger than that during the 1930s-1970s (18%). It is shown that the volume of the Alpine glaciers has decreased by about 29% or 57±20 km^3 for the period 1870s-1970s. The mean rate of changes in the total area, the total volume and area weighted mean thickness of Alpine glaciers for the period 1870s-1970s is -15 km^2/a, and -0.574 km^3/a and -0.163 m/a, respectively.

TABLE 4 Change in area ΔS and volume ΔV of the Alpine glaciers for the period 1870s-1970s S: the present area; V: the volume in the 1970s; $\Delta V/(V+|\Delta V|)$: the relative volume change; and $<\Delta h>/\Delta t$: the mean rate of change in the mean thickness.

Region	S [km^2]	ΔS [km^2]	V [km^3]	ΔV [km^3]	$\Delta V/(V+\|\Delta V\|)$ [%]	$<\Delta h>/\Delta t$: [m a^{-1}]
France	417	-223±25	17.0±3.2	-8.2±6.4	-33	-0.155
Switzerland	1342	-476	79.3±9.1	-27.9±18.2	-26	-0.177
Austria & Germany	543	-452	21.9±2.0	-9.9±4.0	-31	-0.150
Italy	607	-308±29	22.0±1.9	-11.3±3.8	-34	-0.174
Sum	2909	-1459±57	140.1±10.2	-57.4±20.4		
Mean					-29	-0.163

TURNOVER TIME OF AN ALPINE GLACIERS' MASS

The turnover time of an Alpine glacier's mass τ_g is important in investigating the water cycle of a basin with glaciers. τ_g can be defined as the ratio of the volume to the rate of mass output and it can be expressed as:

$$\overline{<\tau_g>} = \overline{<h>}/\overline{<ma>} \tag{7}$$

with $<h>$ being the mean thickness of the glacier and $<ma>$ the annual mass turnover. A bar specifies the mean over time. $<ma>$ is

$$<m_a> = (<b_{ac}> + |<b_{aa}>|) / 2 \tag{8}$$

where $<b_{ac}>$ and $<b_{aa}>$ are the annual balance in the accumulation area and ablation area. Both are averaged over the entire glacier. The specific annual mass turnover $<m_a>$ of 14 Alpine glaciers is calculated from the available data (Kasser, 1967, 1973; Müller, 1977; Haeberli, 1986; Haeberli et al, 1988). The mean $<m_a>$ of 14 Alpine glaciers is 520 mm w. e./a (mm water equivalent per year) with the standard deviation being 278 mm w. e..

The turnover time of an Alpine glaciers' mass is estimated from equation 7 whereby a reference value of $<m_a>$ of 520 mm w. e./a is used. The mean time needed for an Alpine glacier to renew its mass totally is estimated to be 30-60a for a glacier with the surface area S = 0.1-1.0 km^2, 100-120a for one with S = 5.0-10.0 km^2, and 200-240a for one with S = 50.0-100.0 km^2.

CONCLUSIONS AND PERSPECTIVES

The general changes of the Alpine glaciers can be approximately summarized as follows for the period 1870s-1970s: The ice-covered area of the Alpine glaciers was 4368±54 km^2 in the 1870s, 3541±33 km^2 in the 1930s, and 2909 km^2 in the 1970s. For the period 1870s-1970s, the volume of Alpine glaciers decreased by 57±20 km^3 while the volume in the 1970s is 140.1±10.2 km^3. The mean rate of changes in the total area, the total volume and the mean thickness of Alpine glaciers for the period 1870s-1970s are approximately -15 km^2/a, -0.574 km^3/a and -0.163 m/a, respectively. The estimated mass turnover time of an Alpine glacier is in the order of 10^1-10^2a.

At present, the volume - area relationship is widely applied in glacier inventory and water resources estimation due to its simplicity. However, such volume - area relationship should be improved as more accurately measured volume data become available. It is necessary to establish different volume - area relationships according to the type of mountain glaciers (cirque glacier, hanging glacier, valley glacier etc.). In addition, the surface slope of a glacier should be involved in future investigations for estimating the thickness and volume. Because the absolute error of volume estimation increases with the size of the glacier, the volume of larger glaciers (S>20 km^2) should be individually estimated.

ACKNOWLEDGEMENT Dr. W. Haeberli of the World Glacier Monitoring Service has given kind permission for the access to the data base of the Alpine glacier inventory. Dr. P. Müller helped with the transfer of the glacier inventory data. We would also like to express thanks to Mr. M. Aellen and the colleagues of the Department of Geography, Swiss Federal Institute of Technology in Zürich for the discussions and assistance.

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