Some Models of Ice Melt on High Level Lakes in Southwest Norway

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ABSTRACT: Snow and lake ice melt conditions in remote parts of the world are generally not well known. An attempt to understand such conditions at 120 high-altitude lakes in southern Norway was made through a combination of the interpretation of Landsat MSS imagery and the collection of basic topographic and meteorological data. A logistic regression model approach was adopted to develop predictive models for lake ice melt during nine study periods. The models were very successful in predicting the onset of lake ice melt and, as such, should be of value to water resource management and, in particular, to hydroelectric power production in Norway.

INTRODUCTION

THE PURPOSE of this study was to develop regression models to explore the relationships between the state of lake ice melt, as determined by Landsat imagery, and to develop a set of cartographic and meteorological data for relatively remote Norwegian sites. Our findings confirm the recently reported suggestion by Palecki and Barry (1986) that satellite imagery has a significant role to play in monitoring lake ice break-up and is potentially an important tool in the study of regional climates.

The thousands of lakes which festoon the glaciated *vidda* of Norway are a major national resource. Not only do they provide a valuable storage system of potential energy for the highly developed hydroelectric power grid, but they are also locally important for both summer and winter recreation and transport.

There are, of course, conflicting demands on this resource, and power companies wishing to draw off lake water or change water courses often meet with a vociferous challenge from the outdoor lobby. Above all, there is intense interest in the environment and its changing seasons and the problems and prospects they bring.

Winter conditions are difficult in Norway and, consequently, there is a general lack of detailed field monitoring of environmental conditions defining the melt of lake ice. One notable exception is Tvede's detailed heat budget analysis of Lake Mjøsa, Norway's largest lake (Tvede, 1978). This study was part of a monitoring program by the Norwegian Water Resources and Electricity Board which has monthly access to a number of data loggers, to gain information on the lake's heat budget, supplemented by local meteorological information. But Lake Mjøsa is only some 121 m above sea level some 75 km north of Oslo and hardly represents typical conditions to be found on the high mountain plateau of south-western Norway.

In some countries, detailed local records of the dates of lake freeze-up and ice break-up are available and, when married to suitable meteorological data, provide the basis for the development of predictive models. Palecki and Barry (1986), for example, describe such data in their regression modeling study of 63 Finnish lakes, while Ruosteenoia (1986) has developed regression models, based on historical data, for ice break-up on one large lake in central Finland.

Without the possibility of adequate lake instrumentation or on-site observations, one feasible way to gain insight into the environmental controls of lake ice melt is a broad brush approach using remote sensing and various types of readily available geographical data which can be incorporated into a predictive model. There is now a large body of literature describing the use of satellite imagery for snow and ice studies (Hall and Martinec, 1985; Rango, 1985; Skorve, 1977), and, as Palecki and Barry (1986) indicate, satellite imagery can be used to monitor ice growth and decay on lakes on a consistent, regular basis with a uniform approach. The specific interest of the methods described in the present paper is the use of logistic regression models which are an appropriate tool for those situations where the dependent variable is dichotomous. In our case the dichotomy is between those lakes interpreted from satellite imagery as frozen and those which had commenced thawing.

THE STUDY AREA

Geographically, the study area is situated on the 60°N parallel, between Bergen and Stavanger (Figure 1). The area was chosen not only because of its convenient position in relation to Landsat's orbital coverage and because of the existence of a high altitude meteorological station, but also because snow conditions are relatively well known due to the presence of several well monitored glaciers and important hydroelectric power stations.

Geomorphologically, the region is part of the Hardangervidda, the largest mountain plateau in northern Europe. The *vidda* of Norway are relic Tertiary surfaces cut across Precambrian and Lower Paleozoic igneous and metamorphic terrain. In the Quaternary glaciations, ice denuded the vidda of Tertiary

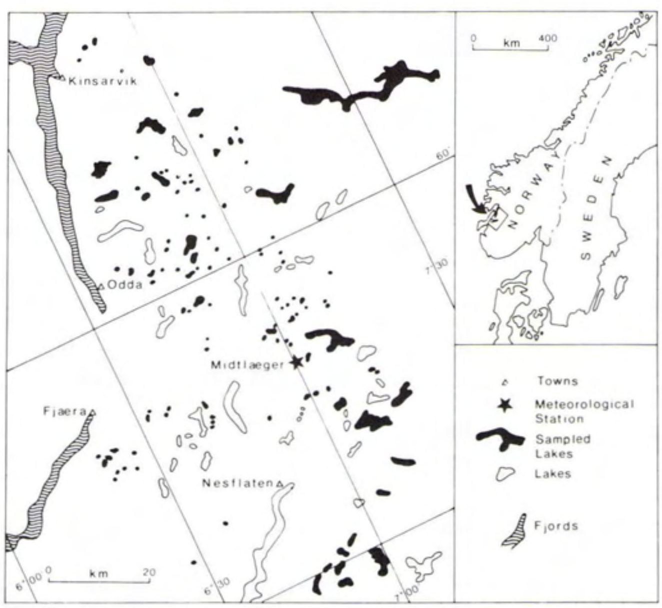

FIG. 1. Location of the study area and the lakes examined.

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weathering products and exposed complex rock structures which now harbor literally thousands of lakes. Along the margins of the *vidda* ice poured off these scoured upland surfaces and deepened valleys to produce the now spectacular glaciated landscape.

The lakes chosen for study lie above the timberline between 882 and 1563 m above sea level and are shown on Figure 1. Immediately to the north and west of the region lie two of Norway's major ice caps, the Hardangerjøkulen and Folgefonna, whose areas are 78 and 212 km², respectively.

CLIMATOLOGY

The climate is quite variable from season to season; for this reason alone we chose to examine ice melt conditions in an eight-year period during which we believe most types of winter conditions prevailed. The general synoptic pattern is relatively straightforward with northeasterly tracking depressions coming in off the Norwegian Sea intersecting a north-south topographical barrier. In the southwest part of the study region annual precipitation is in excess of 2500 mm while in the northeast precipitation is less than 800 mm and the climate is markedly more continental. In addition to this general trend, there are often considerable local variations in precipitation due to topographic control.

Although the network of meteorological stations in Norway is rather dense, there are few located in remote high mountain areas. In our study area we were fortunate that the Midtlaeger station, at 1079 m above sea level on the main Bergen to Oslo road, occupied a fairly central geographical location and was kept open all year. The Mid-laeger station probably received less than the average precipitation for the region, but it still provided the most reliable data for high altitude climates in this region of Norway. Monthly normal precipitation and temperature figures for Midtlaeger are given in Table 1. The study period, 1975 to 1983, was, however, some 22 percent wetter than average.

At this altitude an appreciable amount of precipitation comes as snow and there is a considerable annual variation in precipitation from this source (Table 2). Likewise, during the period 1975 to 1983 there was much variation in the amount of energy available for snow melt as measured by accumulated degree days (Table 3).

Altitudinal air gradients for this part of Norway have been described by Green and Harding (1980). Their analyses suggest that mean gradients are slightly lower than the 7°C used in this paper, but their estimates have fairly large standard errors. Our choice of lapse rate was based on the experience of Olav Liestol (pers. comm) who has taken annual glaciological and meterological measurements in the area since the 1940's.

DATA ACQUISITION

In order to structure lake ice melt as a regression model, we need to measure both ice melt (the dependent variable) and a

TABLE 1. MONTHLY NORMAL PRECIPITATION (MM) AND TEMPERATURE (°C) FOR MIDTLAEGER, 1079 METRES ABOVE SEA LEVEL.

Precipitation in mm											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
85	70	50	55	45	80	110	115	125	120	95	100
Temperature °C											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
−6.1	−6.4	−5.6	−2.3	2.7	6.5	9.5	9.2	5.2	1.0	−2.1	−4.1

TABLE 2. ANNUAL PERCENTAGE OF PRECIPITATION FALLING AS SNOW AT MIDTLAEGER.

Year	1975	1976	1977	1978	1979	1980	1981	1982
Total Precipitation	1133	920	1202	1165	1354	1354	1192	1448
Percent as snow	47	54	40	37	41	29	38	45

TABLE 3. DEGREE-DAY TOTALS FOR MIDTLAEGER.

Year	Accumulated Degree Days (DD)	Deviation from Normal in Percent
1975	1156.1	+ 5.0
1976	1072.0	− 2.7
1979	912.8	−17.1
1980	1240.6	+12.7
1982	1109.3	+ 0.7
1982	1007.2*	+ 7.6
NORMAL	1101.3	

*Records up to the close of the meteorological station on 31 Oct 1983.

TABLE 4. DATES OF LANDSAT SCENES USED IN THE STUDY.

1. 9 Jul 1975	4. 9 Aug 1976	7. 9 Jul 1983
2. 28 Jul 1975	5. 18 Aug 1976	8. 10 Aug 1983
3. 14 Aug 1975	6. 28 Aug 1976	9. 26 Aug 1983

set of explanatory (independent) variables. A sample of 120 lakes was chosen for this investigation, ranging in size from 0.19 km² to 6.0 km². All Landsat imagery of the study area from 1975 to 1983 was scrutinized for suitable cloud free imagery, and nine scenes were chosen for analysis (Table 4). Copies of MSS bands 5 and 7 were obtained as 1:1,000,000-scale negative transparencies together with bands 4 and 6 for some periods. With the negative transparencies as the basis, the following additional products were made: positive contact copies of the transparencies; positive transparencies enlarged to 1:250,000 scale; false color positive transparencies of 2 to 4 multispectral bands on 6- by 6-cm or 6- by 9-cm film with variable scale; and positive single band paper copies of variable scales. The false color enlargements were made with the aid of an additive color viewer.

MSS 5 was the band found most useful for snow and ice mapping. For each Landsat scene the ice situation of all lakes in the sample was systematically mapped onto transparent plastic film. Bolsenga (1983) discusses the spectral reflectance of various types of snow- and ice-melt condition and we found that differentiation of ice-free lakes from ice-covered and partially ice-covered lakes was relatively easy. On one occasion we had the opportunity to verify our Landsat interpretation because a 1:40,000 vertical air photo had been taken in the Midtlaeger area just two days prior to a Landsat pass.

For each of the 120 lakes in the sample and for each time period, the imagery products were examined to ascertain whether or not the lake had started to melt (Figures 2 and 3). If the lake was frozen over, it was coded 0 in our data set; otherwise, it was coded 1. In addition, for each lake, a number of independent variables was obtained from maps which were thought to be relevant to the modeling program. These are listed in Table 5.

Because of the centrality of the Midtlaeger meteorological station, we chose to obtain degree day estimated (DD) by the following formula:

$$DD = DD_M - ((((A - 1079)1/100)0.7)N)$$

where

DD	=	accumulated degree-days for any given lake and date;
DD_M	=	accumulated degree-days at Midtlaeger at a given date;
A	=	the lake altitude above sea-level in metres;
1079	=	the altitude of the Midtlaeger meteorological station;
0.7	=	lapse rate, °C/100 m; and
N	=	number of days since spring melting started at Midtlaeger.

The values for DD_M were obtained from the Meteorological Institute in Oslo.

FIG. 2. Northern part of study area shown on a 50- by 70 km-section, Landsat 4, MSS 5, 10 August 1983. The main fjord shown is Sorfjorden, the southern arm of the Hardangerfjord.

FIG. 3. The same scene on 26 August 1983. Lake ice and snow cover changes are clearly detectable.

TABLE 5. DEFINITION OF VARIABLES USED IN THE REGRESSION MODELS.

AL	- lake altitude in m
LA	- lake latitude
LO	- lake longitude
AR	- lake area (km^2)
RE	- relative relief in drainage basin (m)
RI	- number of rivers flowing into lake
GL	- presence or absence of glacier in drainage basin (0,1)
DD	- accumulated degree days for lake at image date.
S	- percentage snow covered terrain in drainage basin.
L	- lake frozen or not (0,1)

THE LOGISTIC REGRESSION MODEL

The model we wish to examine comprises the binary response, L, lake completely frozen or not, and a number of predictor variables which we have described in the previous section. The dependent variable, L, can be thought of as the number of successes in $n=1$ trials and is thus a Bernoulli random variable; we note that the binomial distribution can be formulated as the sum of n independent Bernoulli random variables. The "success" probability, L, is constrained to $0<L<1$; to ensure that predicted values of the dependent variable are not out of this range we define the logit transformation:

$$\theta = \ln \frac{L}{1 - L} \quad (1)$$

where θ is the linear predictor (LP) and is made up of one or more independent variables. For example,

$$\theta = \text{LP} = \beta_0 + \beta_1 \text{ DD} \quad (2)$$

Solving equation (1) for L and re-writing equation 2, we have

$$L = \frac{e^{\text{LP}}}{1 + e^{\text{LP}}}.$$

With a Binomial response variable it is not appropriate to use conventional least-squares methods. A preferred method is a maximum likelihood iteratively weighted least-squares approach; for this study iterative solutions were found using the widely available Generalized Linear Interactive Modeling statistical package, GLIM, versions of which are available for the IBM PC (Baker and Nelder, 1978).

Goodness-of-fit for a logistic model fitted in GLIM is assessed by a measure called the scaled deviance, which is a log likelihood ratio. Testing the overall fit of any one model is not straightforward because the behavior of the scaled deviance is not known (Swan, 1985). However, differences in scaled deviance between models are chi-square variables and so the importance of any single explanatory variable can readily be assessed.

For each explanatory variable added or subtracted from the regression model, there is a loss or gain of one degree of freedom, respectively. It is useful to note that $\chi^2_{1,0.05} = 3.84$.

There are several ways of producing a parsimonious logistic regression model. We might fit all the independent variables and subsequently drop non-significant estimates, or we might examine the parameters individually and build up to a suitable model. We have chosen the later method in developing the models presented here. We can judge the overall effectiveness of the regression model by simply evaluating the number of correctly predicted assignments because, by convention, we can use $L=0.5$ as a probability threshold between lakes frozen and lakes not frozen.

One of the fundamental problems encountered in handling the data set was multicollinearity. In particular, there are significant linear correlations between percent snow melt (S) and the number of degree days (DD), and between lake area (AR) and number of rivers entering the lake (RI). For each model, we have used that variable which reduced the scaled deviance most, but in practically all cases substitution of one or the other of the correlates hardly affected the overall predictive properties of the model.

RESULTS AND DISCUSSION

The results from the logistic regression modeling exercise are presented in Tables 6 through 8. In terms of their ability to predict whether or not a lake is frozen or not, the nine regression models described in Tables 6 through 8 are remarkably successful. This is in spite of the fact that the winter conditions were very different in the three years examined, with 1983 having quite exceptionally heavy snowfall. Summer conditions were reasonably similar and, over the period of the Landsat imagery examined, the mean daily increase in degree day temperatures for 1975, 1976, and 1983 was 11.95°C, 12.33°C, and 11.97°C, respectively. One would of course expect variables such as accumulated degree days, snow cover, and perhaps lake area to influence the thawing of lake ice, and in that sense our results are rather expected.

In all models either degree days or the percent snow in the catchment area has proven to be an important explanatory variable, and degree day extrapolations from the Midtlaeger station proved remarkably good at predicting snow wastage for almost all basins in the study area. It is a great pity that this station

TABLE 6. LOGIT REGRESSION MODELS FOR 1975.

Estimate	Standard Error	Parameter
9 July 1975		
120.70	63.20	Intercept
−1.94	0.99	*S*
Prediction success 97 percent		
28 July 1975		
−83.25	33.94	Intercept
0.04	0.01	BB
12.19	4.34	LO
−0.01	0.00	RE
−0.25	0.06	*S*
1.98	0.73	AR
Prediction success 85 percent		
14 August 1975		
−1.16	2.91	Intercept
0.01	0.00	DD
−0.11	0.03	*S*
6.28	2.14	AR
Prediction success 87 percent		

TABLE 7. LOGIT REGRESSION MODELS FOR 1976.

Estimate	Standard Error	Parameter
9 August 1976		
−30.78	12.33	Intercept
3.44	1.59	LO
2.60	1.20	AR
0.01	0.00	DD
−0.01	0.00	RE
Prediction success 83 percent		
18 August 1976		
46.29	20.21	Intercept
16.70	6.92	AR
−2.71	1.52	GL
−0.66	0.25	S
Prediction success 99 percent		
27 August 1976		
−7.05	3.01	Intercept
5.70	2.99	AR
0.01	0.00	DD
Prediction success 93 percent		

TABLE 8. LOGIT REGRESSION MODELS FOR 1983.

Estimate	Standard Error	Parameter
9 July 1983		
30.54	13.48	Intercept
−0.02	0.00	S
Prediction success 99 percent		
10 August 1983		
−36.09	17.10	Intercept
4.26	2.06	LO
2.76	1.05	AR
−0.0.5	0.01	S
Prediction success 87 percent		
26 August 1983		
2.89	0.82	Intercept
5.09	1.50	AR
−0.07	0.01	S
Prediction success 83 percent		

was closed down in October 1983 as it is clearly a key site from which snow melt might be predicted. In fact, the station was moved further east to Haukeliseter, also on the main road between Oslo and Bergen but this site is less suitable for our purposes because of its more continental climate. Predictions of lake ice melt in the study area needed are by the State Water Authority, but the high cost of running the Midtlaeger station forced its closure and removal to a more accessible site.

Area (AR) was almost as persistent a factor in the regression models as snow cover and degree days, the positive sign of the parameter estimates indicating that the probability of melt increases with lake size. However, as we noticed previously, there is a general linear relationship between number of rivers entering a lake (RI) and lake size. To what extent this meltwater brings heat to the lake or merely disturbs the steady winter and early spring thermal profiles of the lake is not known, and our data are limited in the sense that we counted only blue lines (rivers and streams) on maps and have no knowledge about discharges. The picture is made even more complicated by the fact that larger lakes will almost certainly be more exposed and be subjected to greater adjective heat transfer at the ice-air interface. Notwithstanding all these complications, simple map data have proved to be very cost effective in the development of a predictive model of ice melt as compared with detailed heat budget studies requiring both instrumentation and manpower.

In one instance, 18 August 1976, our model detected the influence of local glaciers (GL) on the melt. This variable was set up in GLIM as a factor, which means that it was used to set up a dummy variable structure to examine the covariance of regressions associated with two subsets of the data, those lake basins containing glaciers and those without. On this occasion, GL was significant at the .05 level, the sign of the parameter estimate estimate indicating that the presence of a glacier in the lake catchment lowered the probability of the lake ice having started to melt. Possible mechanisms to explain this presumably relate to cold air drainage off the glaciers into the lake basin.

On three occasions—28 July 1975, 9 August 1976, and 10 August 1983—the longitude of the lake (LO) was entered into the regression model as an important explanatory variable. In all cases the sign of the parameter estimate indicated that lake melt probability increased in an easterly manner. This is difficult to explain and there are conflicting clues in the data set. For example, for these three periods there are very weak negative trends when percent snow cover is plotted against longitude, and this together with possibly more radiation being received away from the coast might well account for the importance of LO. On the other hand, there is a weak positive relationship between lake altitude and longitude which would obviously run counter to the previous factor. At this point we are in danger of having more hypotheses than data and all we can say is that this problem requires more and better data than those discussed earlier.

The regression models for 28 July 1975 and 9 August 1976 are interesting because they incorporate the relative relief factor (RE) as a significant explanatory variable. On both occasions the increased probability of the lake having melted is associated with lake basins of lower relative relief. Intuitively, this seems very reasonable. Not only might high relative relief induce cold air drainage and cloudiness due to orography but might also effectively act as a barrier to the penetration of an ameliorating wind.

It is of some interest to relate our findings with those of Palecki and Barry (1986) who had access to detailed on-site observations recording lake ice break-up dates and a rather good network of meteorological stations. It is also worth noting the contrasting environments, the Finnish lakes being in low altitude boreal forest sites while the Norwegian lakes are located in partially glaciated sub-arctic tundra. Both the results of Palecki and Barry and those presented here find strong statistical relationships between ice cover and various air temperature indices. This is not in itself surprising, but the calibration of the predictive models for two very contrasting situations confirms the suggestion by Palecki and Barry that regular monitoring of lake ice conditions provides a useful tool for studies of regional climatic variations. Palecki and Barry also report moderately strong correlations between lake ice break-up and latitude, longitude, and area. These findings are mirrored for area and longitude in our results but not for latitude. This last result is not at all surprising, however, given the relatively small range of latitude in our study area.

CONCLUSIONS

The differentiation of thawing from still frozen high-altitude Norwegian lakes was found to be relatively easy using Landsat MSS band 5 imagery. The simple division of lakes into two classes can give rise to statistical problems if the lake condition is used as the dependent variable in a regression model. In this paper the dichotomy was handled using a logistic regression approach which is specifically designed to overcome difficulties such as predictions of a 0, 1 dependent variable being out range. This approach has wide applications where interval or ratio scale data are not available but simple yes, no assignments can be made. The method has the additional advantage in that the predictions can be regarded as probabilities of assignment to one of the two classes in the dichotomy.

The logistic regression models described in this paper, using simple topographic and meteorological data, were remarkably successful in predicting whether a lake was frozen or not. In particular, the number of positive degree days, the lake area, and the area of snow in the lake catchment proved to be important independent variables. What is perhaps noteworthy is that we have been able to develop models which describe not a single lake but a fairly large sample of lakes in a reasonably heterogeneous area. This suggests that the approach is a fairly robust one and should be widely applicable to similarly glaciated terrain in other parts of the world. Our areal sample was rather restricted but, if the approach were applied more generally in Norway, there is no doubt that lake thaw, as identified through satellite imagery, would be an important tool for the investigation of regional climatic change.

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